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Lower bounds on the exploitation of cod (*Gadus morhua*) in NAFO Divs. 3KL and Subdiv. 3Ps during 1997-1999 from tagging experiments.

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1 Abstract

We develop a model to estimate exploitation rates (fraction of stock removed by the fishery) using tags returned from the commercial fisheries for Atlantic cod in NAFO Divisions 3L and 3K (3KL) and Subdiv. 3Ps and adjacent areas during 1997-1999. The tag-returns are from numerous tagging experiments conducted in these areas during 1997-1999. Over 36 000 cod in total have been tagged and released during 1997-1999 and 4007 of these have been reported as recaptured. Our model involves length- and gear-based exploitation rates and incorporates methods to estimate tagging mortality, tag loss, tag reporting rates, and fish growth. We use this model to estimate weekly exploitation rates in 3KL and 3Ps; however, we focus on exploitation in 3KL during the two time periods in which most of the commercial catch in 1999 was taken: July, and September 5 to October 10.

Emigration of tagged fish complicates the analysis of tag-returns, and can result in underestimation of exploitation rates. The fraction of tagged fish that were released and subsequently returned by the fishery will represent only part of the total exploitation when tagged fish emigrate outside the fishing region. This is because the size of the tagged population available to the fishery is less than the number of tagged fish that were released. At present we have not been able to account for migration in our tagging model. Our estimates represent the fraction of the tagged population exploited by the fishery if there was no migration. The actual exploitation of the fishery is higher than the quantity we estimate. Nonetheless, we feel our results are reasonably accurate for 3K and the northern part of 3L where migration appears low. Our results suggest that exploitation rates in 3K and northern 3L during July of 1999 were 19.4% and 2.3%, respectively. During September 5 to October 10 the exploitation rate estimated in 3K was 13.5%, and in northern 3L the estimate was 3.8%. Using the reported landings for these two periods, we estimate that the biomass of fish in 3K was 9 000 and 11 000 tonnes in July and September 5 to October 10, respectively. The biomass in northern 3L was estimated to be 50 000 and 42 000 tonnes in July and September 5 to October 10. Our results for southern 3L were considered too unreliable because of the extensive movements of fish between this region and 3Ps.

Résumé

Nous avons élaboré un modèle pour estimer les taux d'exploitation de la morue de l'Atlantique (fraction du stock récoltée par les pêcheurs) d'après les données sur les individus étiquetés recapturés par les pêcheurs commerciaux dans les divisions 3L et 3K (3KL) et la sous-division 3Ps de l'OPANO, ainsi que dans les eaux adjacentes, de 1997 à 1999. Les étiquettes récupérées sont issues de nombreuses expériences d'étiquetage menées dans cette région pendant cette période; du total de plus de 36 000 morues de l'Atlantique étiquetées et remises à l'eau, 4 007 ont été déclarées recapturées. Notre modèle met en jeu les taux d'exploitation selon la longueur et les engins et des méthodes d'estimation de la mortalité par étiquetage, du nombre d'étiquettes perdues, des taux de retour des

étiquettes et des taux de croissance du poisson. Nous l'avons utilisé pour estimer les taux d'exploitation hebdomadaires dans 3KL et 3Ps, mais en mettant l'accent sur l'exploitation dans 3KL pendant les deux périodes où la plus grande partie des prises commerciales ont été récoltées en 1999, soit en juillet et du 5 septembre au 10 octobre.

L'émigration du poisson étiqueté complique l'analyse des étiquettes récupérées du fait qu'elle peut résulter en une sous-estimation des taux d'exploitation. La fraction de poissons étiquetés remis à l'eau et recapturés par les pêcheurs ne représente qu'une partie du taux d'exploitation total lorsque le poisson étiqueté émigre à l'extérieur de la pêcherie parce que la taille de la population étiquetée qui peut être pêchée est moindre que le nombre de poissons étiquetés remis à l'eau. Comme nous n'avons pas encore réussi à inclure la migration dans notre modèle de l'étiquetage, nos estimations représentent la fraction de la population étiquetée exploitée par les pêcheurs en l'absence d'une migration. Le taux réel d'exploitation par pêche est donc plus élevé que le volume que nous avons estimé. Nous considérons toutefois que nos résultats sont suffisamment précis dans le cas de 3K et de la partie nord de 3L, où la migration semble faible. Ils laissent supposer que les taux d'exploitation dans ces deux pêcheries en juillet 1999 se chiffraient à 19,4 % et 2,3 %, respectivement, tandis que du 5 septembre au 10 octobre, ils se situaient à environ 13,5 % dans la division 3K et 3,8 % dans la partie nord de 3L. En nous servant des débarquements signalés pendant ces deux périodes, nous avons estimé que la biomasse du poisson dans 3K atteignait 9 000 t et 11 000 t en juillet et du 5 septembre au 10 octobre, respectivement. La biomasse dans la partie nord de 3L atteignait 50 000 t et 42 000 t pendant ces périodes. Nous considérons les résultats obtenus pour la partie sud de 3L comme douteux à cause des déplacements de grande envergure du poisson entre cette région et 3Ps.

2 Introduction

It is possible to estimate the exploitation rate (fraction of stock removed by the fishery) by a commercial fishery using data from fish tagging experiments. Essentially, the fraction of tags caught in a commercial fishery and returned by fishermen provides an estimate of the fishery exploitation rate, assuming that the fishery equally exploits tagged and un-tagged fish. The exploitation rate can then be used, in conjunction with estimates of the total landings by the fishery, to estimate stock size.

In practise the analysis of tagging experiments is complicated by many factors:

1. Although fishermen are encouraged using rewards to return tags, not all tagged fish caught by the fishery are reported. This means that the percentage of returned tags will underestimate the exploitation rate, because some fish with tags will have been caught but the tags not returned.

2. The number of tagged fish available for capture decreases with time because of tag loss and migration of tagged fish out of the fishing region, as well as natural

mortality and previous removals by the fishery. This also means that the percentage of returned tags will underestimate the exploitation rate, because the size of the tagged population available to the fishery is less than the size of the tagged population released.

3. Exploitation rates vary with fish size because the fishery tends to be size selective. This also depends on the gear types used by fishermen. If the size distribution of the tagged population is not the same as the size distribution of the total population, as is usually the case, then the selectivity of the fishery is important to understand when computing total exploitation (see **Section 3.1**). Size in cod fisheries is usually taken as length. To estimate selectivity we need to know the length composition of the tagged population, which will be different from the length composition at the time of release because of fish growth; hence, knowledge of fish growth rates is important for estimating exploitation rates.

4. Exploitation rates vary within and between years because of different quotas and seasonal closures or restrictions on the fishery, but also because of seasonal movements of fish within fishing zones; that is, the size of the population being exploited also changes within and between years. Typically the putative populations considered for fisheries management are not closed. Management strategies are increasingly becoming focused on the preservation of sub-stock structure, and knowledge of within year exploitation rates and seasonal movement rates is important to achieve this management goal.

In this paper we develop a model to estimate fishery exploitation rates for Atlantic cod in NAFO Divisions 3L and 3K (3KL) and Subdivision 3Ps and during 1997-1999 using tags returned from the fishery. The tag-returns are from numerous tagging experiments conducted in 3Ps and 3KL during 1997-1999. Many of these experiments are described in Brattey et al. (1999) and Brattey (2000). Our model incorporates length- and gear-based fishery selectivity, and also incorporates methods to estimate tagging mortality, tag loss, tag reporting rates, and fish growth. We use this model to estimate weekly exploitation rates for the cod fisheries in 3KL and 3Ps; however, we focus on exploitation in 3KL during the two time periods in which most of the commercial catch in 1999 was taken: July, and September 5 to October 10.

Emigration of tagged fish complicates the analysis of tag-returns, and can result in underestimation of exploitation rates. When tagged fish emigrate outside the fishing region, the fraction of tagged fish that were released and subsequently returned by the fishery will represent only part of the total exploitation. This is because the size of the tagged population available to the fishery is less than the number of tagged fish that were released. Coarse estimates of migration and exploitation rates were presented in Cadigan and Brattey (1999a); however, we have not been able to extend their approach to the model we use in this paper, so our estimates of exploitation rates will be too low. We also do not advocate using the approach in Cadigan and Brattey (1999a) because their coarse treatment of tagging information leads to under-estimation of exploitation

rates in some circumstances. Their approach also did not consider the effects of fishery length-selectivity. Nonetheless, we feel our results are reasonably accurate for 3K and the northern part of 3L where migration appears low.

3 The data

We analyze the tag-returns from 70 tagging experiments conducted in 3Ps and 3KL during 1997-1999. The number of fish released in each experiment ranged from 3 to over 2400, with an average of approximately 500. Over 36,000 fish in total have been tagged and released in 3KL and 3Ps during 1997-1999. From these releases 4007 tags have been returned from fisheries in these regions, and also fisheries in NAFO Divisions 3N and 3O (3NO), 4R-4S and Subdivision 3Pn (4RS-3Pn). The location and other details of these experiments are described in Brattey et al. (1999) and Brattey (2000). Most cod for tagging were captured with hand-lines, but some trap-caught and otter-trawled cod were also tagged. The length of each cod (nearest cm) was recorded. Only cod with a fork length exceeding 45 cm and in excellent condition were tagged and released. For analysis, groups of cod tagged in the same general area over a time frame of a few days to weeks were classified as a single experiment which was assigned a four digit sequential identifier; the first two digits representing the year of capture and the second two digits incrementing annually from 01 onwards (i.e. 9701, 9702...). The locations of experiments are shown in Figure 1 in the **Appendix**.

Fish tagged with various combinations of t-bar anchor tags (Floy) were released simultaneously in the experiments. Low reward ($10, yellow color) and high reward ($100, pink color) tags were used to estimate reporting rates. Fishermen do not return all the low reward tags from fish they capture, for various reasons. If we assume that the high reward is sufficient to ensure complete reporting then the return rate for this type of tag can be used to estimate the reporting rates for low reward tags. Solely high reward tags were not used because the reward costs would be prohibitive. Some fish (approximately 40%) were also double tagged (with two low reward tags), and the proportion of such fish caught over time with only one tag can be used to estimate the rate of tag loss (for more details see Cadigan and Brattey, 1999b).

For our analysis we have grouped capture times into weeks. We grouped capture locations into eight broad geographical regions (see Figure 1 in the **Appendix**). The regions are:

Number	Region ID	Unit Area
1	3K_IN	3Kd, 3K(h-i)
2	3L_INN	3L(a-b)
3	3L_INS	3Lf, 3Lj, 3Lq
4	3Ps_PB	3Psc
5	3NO	3N(all), 3O(all)
6	3Ps_OF	3Ps(f-h)
7	3Ps_WB	3Ps(a-b), 3Ps(d-e)
8	3Pn_4RS	3Pn, 4R(a-d), 4S(v-w)

These regions were constructed to reflect potential sub-stock structure and spatial variation in exploitation rates.

There are some known problems with these data that we wish to highlight. We suspect that some of the information fishermen supply when they send in a tag is not completely accurate. This is because on several occasions tags have been received with information that we know is not correct. We speculate that sometimes fishermen do not immediately record all the information (length, date, place of capture, etc.) about the tagged fish that they caught, and they guess about some of the required information when they send tags in later. Such guesses can be inaccurate. Otherwise some fishermen simply do not report all of the requested information. For example, in our tag return data base there are

1. missing lengths-at-capture and errors in lengths-at-capture ($\sim 50\%$),
2. missing capture weeks ($\sim 17\%$),
3. missing unit areas of capture ($\sim 1\%$), and
4. missing gear-type used to catch the fish ($\sim 13\%$).

We address the first problem by utilizing a growth model to predict lengths-at-capture from known lengths-at-release and times-at-liberty. The model is developed in Cadigan and Brattey (2000). In this paper we use the growth estimates from the model depicted in Figure 17 in Cadigan and Brattey (2000). We use an imputation procedure to deal with missing capture regions and weeks. This procedure is described in the next section. For the last problem we simply treat missing gear types as another type of gear. Otherwise, in our analyses we do not account for measurement errors in the reported capture information supplied by fishermen. We feel that such measurement errors are a relatively minor detail compared to other modelling issues that are associated with the tag-return data.

3.1 Imputation of capture-region and week

Imputation involves estimating a missing value. It is easier to first describe the imputation procedure we use for missing capture-regions. The procedure we use is to select some relevant covariates that are available for a tag-return with a missing region, and examine the capture regions for other tag-returns with the same values for the relevant covariates

(i.e. matches). The imputation involves assigning the missing region as the modal known capture-region from the matches. The relevant covariates we used are *experiment*, *gear-type*, and *capture-time*. The rationale for choosing *experiment* as an imputation covariate is that fish from particular experiments tend to be caught only in a subset of the eight regions listed above. This is because an experiment is a cluster of fish that tend to behave more similarly in terms of migration than do fish between experiments. Therefore, if we know which *experiment* the tag-return without a recorded region came from then we can isolate a few "more likely" capture regions. Similarly, only some gears are used at any time in these regions. For example, if we know that fish from experiment x only move to regions 1, 2 and 3, and at time t only gillnets were used in region 2, then a tag-return at time t from experiment x caught with a gillnet must have been caught in region 2. In practise the imputation procedure rarely selects only one capture-region, and in these cases the modal capture-region is used as an estimate.

Sometimes no matches are selected. This is a problem when too many covariates are used for matching. In this case we drop one covariate and re-run the imputation procedure. If no matches are found we first replace *experiment* by *release-region*, and if no matches are still found then we drop *release-region* and match only on *capture-time* and *gear-type*. Matches were always found with these two covariates.

A similar imputation procedure was used for missing capture weeks, with some differences however. Varying degrees of "missingness" exist with capture times. Quite often we know the month-of-capture, but not the week. Sometimes only the year-of-capture is reported. We always know the time-of-release and the time that the tag is returned to DFO. Using this information we can fix a lower and upper bound on the capture-week. Our imputation procedure is to match on these bounds, and also to match on *length-at-release*, *gear-type*, and *experiment*. If no matching occurs then we replace the imputation covariate *experiment* with *release-region*, and if no matching still occurs then we drop *length-at-release*. If no matching occurs at this level then we simply estimate the capture-time as the mid-point between the bounds on capture-time. Note that when imputing capture-region we used the bounds on capture-times if the exact capture-week was missing.

4 Model

In this section we describe the model we use to estimate exploitation rates from tag-return data. We start with a description of our model when applied to very simple tag-return data, then we adapt this model to accommodate the complexities of the tag-return data for the 3KL and 3Ps fisheries.

4.1 Simple model

The rate that tags are returned is a function of the exploitation rate (μ) of the commercial fishery, which is the fraction of fish removed by the fishery:

$$\mu = \frac{C}{N}, \tag{1}$$

where C is the commercial catch and N is the population size. If we know μ and C then we can estimate N,

$$\hat{N} = C/\hat{\mu}.$$

The advantage of tagging experiments is that we can use them to estimate μ. In the simple situation where a pulse fishery exploits the tagged and un-tagged populations equally, and all tags found by fishermen are reported, and we know the size of the tagged population (M), then the number of tag-returns (R) has expectation $E(R) = \mu M$. We can estimate μ using the observed number of tag-returns (r),

$$\hat{\mu} = \frac{r}{M}.$$

Just knowing C in (1) does not allow us to estimate μ because we do not know N. A tagging experiment allows us to monitor the commercial fishery removals from a population of known size (i.e. M), and this provides information to estimate μ.

If the fishery occurs over time intervals that we observed catches from (C_1, C_2, C_3, ...) then we can estimate the exploitation rate at each time interval using a single tagging experiment. If the population is closed and experiences only fishing mortality, then

$$\hat{\mu}_1 = \frac{r_1}{M},$$
$$\hat{\mu}_2 = \frac{r_2}{(1-\hat{\mu}_1)M},$$
$$\hat{\mu}_3 = \frac{r_3}{(1-\hat{\mu}_1)(1-\hat{\mu}_2)M}, \text{ etc.}$$

If the population is not closed and emigration occurs, or the population experiences non-fishing mortality or tag loss so that only a fraction q_i of the tagged population remains between times $i-1$ and i, then

$$\hat{\mu}_2 = \frac{r_2}{(1-\hat{\mu}_1)q_2M},$$
$$\hat{\mu}_3 = \frac{r_3}{(1-\hat{\mu}_1)(1-\hat{\mu}_2)q_3M}, \text{ etc.}$$

In these situations we need to know the q's to estimate exploitation rates. If tagging experiments occur at each of the time periods then it is possible to estimate the q's.

With length selection the situation is more complicated. The exploitation at length l is

$$\mu_l = \frac{C_l}{N_l}.$$

However, total exploitation is not just the average of μ_l's; that is,

$$\mu = \frac{C}{N} = \frac{\sum_l C_l}{\sum_l N_l} = \frac{\sum C_l}{\sum_l C_l/\mu_l} = \frac{1}{\sum p_l/\mu_l},$$

where $p_l = C_l/\sum_l C_l$. To estimate total exploitation we need to estimate the μ_l's for all exploited length classes, and we also need to estimate the length distribution of the catch (i.e. the p_l's). The statistic R/M is an unbiased estimator of μ only if the length distribution of the tagged population is the same as the length distribution of the population; that is,

$$\frac{M_l}{\sum_l M_l} = \frac{N_l}{\sum_l N_l}.$$

In this case

$$\frac{E(R)}{M} = \frac{\sum_l \mu_l M_l}{\sum_l M_l} = \sum_l \mu_l \left(\frac{M_l}{\sum_l M_l}\right) = \sum \mu_l \left(\frac{N_l}{\sum_l N_l}\right) = \frac{\sum_l C_l}{\sum_l N_l} = \frac{C}{N}.$$

If fish are selected at random from the population so that $E_{M_l|M}(M_l/M) = N_l/N$ then $E_{M_l|M}\, E_R(R/M)$ is also equal to μ.

4.2 Realistic model

In this section we develop the model we use to estimate exploitation rates for the fisheries in 3KL and 3Ps. The commercial fisheries in these regions are substantially more complicated than the more simple examples we considered in the previous section; however, the methods extend in a straightforward manner. The exploitation rates in 3KL and 3Ps vary with fish length, region, gear-type and time. Let μ_{glti} denote the exploitation rate ($0 \leq \mu_{glti} \leq 1$) by gear type g during week t, for fish of length l in region i. Exploitation is defined as

$$C_{glti} = \mu_{glti} N_{lti}, \tag{2}$$

where C_{glti} is the commercial catch and N_{lti} is the population size. Both μ_{glti} and N_{lti} are unknown. If we can estimate $\mu_{lti} = \sum_g \mu_{glti}$ then we can also estimate N_{lti} if we have information about C_{glti}. However,

Remark 1 *our estimates of exploitation rates are independent of the reported landings by the commercial fishery.*

If our modelling assumptions are correct then our estimates of exploitation rates are valid even if the reported landings are inaccurate. Mis-reported catches only affect our estimates of stock size.

The tags returned by the commercial fishery are a small subset of C_{glti}, but nonetheless they come from the same capture process. If R_{xglti} is a random variable for the number of tags returned from experiment x and gear type g during week t, for fish of length l in region i, then assuming complete reporting and no tag loss,

$$E(R_{xglti}) = \mu_{glti} M_{xlti}, \tag{3}$$

where M_{xlti} is the number of tagged fish in the population from experiment x that are in region i at time t. We can estimate M_{xlti} because we know the number of fish that were released (see below). Having estimated M_{xlti} we can also estimate μ_{glti}, and use this estimate with information about C_{glti} to estimate N_{lti}.

We use a separable multiplicative model for exploitation rates:

$$\mu_{glti} = \mu_{gti} s_{gli}. \tag{4}$$

Essentially (4) decomposes μ_{glti} into a region/week/gear effect (μ_{gti}) and a region/gear length-selection effect (s_{gli}). We model $\ln(s_{gli})$ using a quadratic polynomial approximation, constrained so that $\max_l s_{gli} = 1$ for each gear-type g and region i. We assume that gear selectivity is independent of t within a year; that is, gear selectivity does not change within a year. Our assumption that gear selectivity does not change within a year is reasonable as long as the actual types of gears associated with our nominal gear categories do not change substantially; for example, as long as the gillnet mesh size remains the same within years. This assumption may not be reasonable for our "unknown" gear type; however, such gears are involved in only a small part of the total exploitation for cod in 3KL and 3Ps, and estimates of total exploitation will not be very sensitive to assumptions about the selectivity of "unknown" types of gears.

In practise all tags found on fish are not reported. We mentioned in **Section 2** that we can estimate the reporting rates based on releasing some fish with high rewards, and assuming all the high reward tags are returned from captured fish. The reward scheme is well publicized and fishermen are aware of the high reward tags. We have had several low reward tags returned directly to technical staff while conducting field work in fishing communities, but this has not occurred for high reward tags; hence, we feel the assumption about complete reporting of high reward tags is reasonable.

At any time following release there are four types of tagged fish available to the fishery. These are fish with

$$k = \begin{cases} 1, \text{ one low-reward tag from one at release,} \\ 2, \text{ one low-reward tag from two at release,} \\ 3, \text{ two low-reward tags,} \\ 4, \text{ a high-reward tag.} \end{cases}$$

A model relating M_{xltik} (the index k refers to the type of tagged population) in terms of the numbers of single, double, and high-reward releases is presented in Cadigan and

Brattey (1999b). We use the same basic approach in this paper, although with several modifications.

The first modification is that in this paper we estimate single (type I) and double (type II) reporting rates (λ) separately for each region, and assess the statistical significance of differences in reporting rates. We also investigate whether there is significant inter-annual variation is reporting rates.

The second modification involves the tag loss model. We have conducted analyses (unreported) that suggest a better model for the tag loss rate. Tag loss is an increasing function of time-at-liberty $t - t_x$, where t_x is the time-of-release for experiment x and t is the capture week. The model we use in this paper for the probability a tag has not been lost during $t - t_x$ is

$$\phi(t - t_x) = \left(\frac{b}{b + c(t - t_x)}\right)^b,$$

where b and c are tag loss parameters. The basis for choosing this model over the more standard proportional tag loss model $\phi(t-t_x) = \exp[\phi(t - t_x)]$ will be presented elsewhere. We assume the tag loss rate does not depend on region-of-release or region-of-capture, which is reasonable. We also assume that tags on double tagged fish are lost independently of each other, and with the same probability. We have conducted analyses (unreported) that do not suggest the return rate of tags from double tagged fish is related to the position of the tag on the fish. The final modification is that we do not assume any handling loss, which differs from Cadigan and Brattey (1999b). Preliminary analyses indicated that this parameter is not statistically different from zero.

Having estimated reporting rates and tag loss rates we compute the effective total (over tag type) number of tagged fish available to the fishery; that is,

$$M^e_{xlti} = M_{xlti} \times \phi(t - t_x)\left[\lambda^I_{ti} p^s_{xl} + p^h_{xl} + 2\lambda^I_{ti}\left\{1 - \phi(t - t_x)\right\} p^d_{xl} + \lambda^{II}_{ti}\phi(t - t_x) p^d_{xl}\right],$$

where p^s, p^d, and p^h are the proportions released of single, double, and high-reward tags. The effective number is the population number adjusted for reporting rates and tag loss rates. It is a quantity we construct to simplify estimation and inference. We still need to express M_{xlti} in terms of the known number of tagged fish released in experiment x and region i (i.e. M_{xli}). When there is no migration then the number of tagged fish in the population is equal to the number of tagged fish released, discounted for natural mortality and exploitation by the fishery; that is,

$$M_{xlti} = \xi_{xlti} e^{-m(t - t_x)} M_{xli}.$$

In this equation m is the weekly natural mortality rate and $\exp[-m(t - t_x)]$ is the proportion of the population that has not died due to natural mortality, and ξ_{xlti} is the cumulative survival probability up to time t for fish released at time t_x; that is,

$$\xi_{xlti} = \Pi_{j=t_x}^{t-1}(1 - \mu_{lti}),$$

where $\mu_{lti} = \sum_g \mu_{glti}$ is the total exploitation rate during week t, for fish of length l in region i.

With migration the situation is considerably more complex, because the cumulative survival of the tagged population will depend on where fish have migrated; that is, they will have experienced exploitation in all the regions they have visited up to time t. The usual approach in this case is to express the tagged population model in a matrix format (for example see Cadigan and Brattey, 1999a) and project the population forward in time (i.e. weeks) using transition matrices for the migration rates between geographic regions. We have to do this for all experiments and all length classes of fish that were tagged, which is an enormous computational task, especially when the migration rates must be estimated iteratively. We have not been successful in estimating migration rates so far and we continue to research how to do this for complex fisheries like those in 3KL and 3Ps. The best we can currently do is to estimate exploitation rates assuming known migration rates between geographic regions. Our analyses will be limited to the case where no migration occurs; that is, the migrations rates between all regions are zero.

Fish growth also complicates the analysis of tagging data because the exploitation experienced by a fish depends on its length, and fish length increases with time-at-liberty. To model length selectivity we need to know the lengths of tagged fish available to the fishery following release, and not just the lengths of tagged fish at the time of release. The tagging experiments also provide information on fish growth because quite often fishermen measure and report the length of the fish when they catch it. To estimate fish lengths at times following release we estimate a growth model using the lengths-at-capture data. This analysis is presented in Cadigan and Brattey (2000). We simply use the estimated growth model in Cadigan and Brattey (2000) to predict the lengths of all tagged fish for each week following their release throughout 1997-1999, or until a tagged fish is captured.

For estimation and inference about exploitation we assume that R_{xglti} has an overdispersed Poisson distribution, with

$$E(R_{xglti}) = \mu_{glti} M^e_{xlti}.$$

For inferences about selectivity and exploitation rates we simply treat estimates of reporting rates and tag loss rates as fixed. To simplify (and improve) estimation we use a conditional approach for inference about selectivity.

For each experiment, week, gear type, and region combination that we observe tag-returns in, the proportion of returns in each length class l is primarily determined by the selectivity of the gear. Let R_{xgti} be the total number of tags returned in each combination; that is, $R_{xgti} = \sum_l R_{xglti}$. The distribution of R_{xgti} contains little information about selectivity in the absence of information about μ_{gti} in (4). Therefore, we base our inferences about s_{gli} on the conditional distribution of $R_{xglti}|R_{xgti}$. This is a Multinomial distribution, with probabilities

$$\Pr(R_{xglti}|R_{xgti}) = \frac{s_{gli}\xi_{xlti}M^e_{xlti}}{\sum_l s_{gli}\xi_{xlti}M^e_{xlti}}. \tag{5}$$

The multinomial samples are independent between experiments, gears, times, and regions. It is important to keep in mind that s_{gli} is modelled in terms of length-at-capture and not length-at-release. The multinomial probabilities are determined by unknown selectivities and survival probabilities.

Joint estimation of all these parameters is difficult, so we use an iterative approach for estimation. In this approach we

1. fix the ξ's at initial values,
2. estimate s_{gli}'s (and also μ_{gti}'s, see below) using the fixed values for the ξ's,
3. update the ξ's using the estimates of μ_{gti}'s and s_{gli}'s, and
4. repeat steps 2 and 3 until parameter values converge.

Convergence usually occurs in 5-6 iterations. This demonstrates the insensitivity of the distribution of $R_{xglti}|R_{xgti}$ to survival probabilities, and also the insensitivity of the distribution of R_{xgti} to gear selectivity. This "robust" property is an advantage of the conditional approach to inference. An even greater advantage is the computational simplification that results from using the conditional approach.

Inferences about μ_{gti} are based on the marginal distribution of R_{xgti}. This has a Poisson distribution, with expectation

$$E(R_{xgti}) = \mu_{gti} d_{xti}, \tag{6}$$

where $d_{xti} = \sum_l s_{gli} \xi_{xlti} M^e_{xlti}$. Note that if selectivity is constant and survival is approximately one then $d_{xti} = \sum_l M^e_{xlti}$ is just the total effective number of tagged fish, and (6) has the same form as (3). We treat the selectivity parameters as fixed when making inferences about μ_{gti}. Estimation of the μ_{gti}'s involves a straightforward application of generalized linear models (GLIM's, see McCullagh and Nelder, 1989). We used PROC GENMOD is SAS for this purpose, with CLASS variables *week* nested within class variables *gear* and *region*. We used the log link function $\ln[E(R_{xgti})] = \ln(\mu_{gti}) + \ln(d_{xti})$, in which case $\ln(d_{xti})$ is treated as an offset variable.

A factor that we have not considered so far is tagging-induced mortality. It may be that only a fraction of the number of fish that were tagged actually survive long enough to be exploited by the fishery. Let τ denote the probability of surviving tagging. We can estimate τ by using the results of experiments that involve the retention of tagged and untagged cod in large (3 x 2 x 2m) submersible enclosures for various periods of time; several experiments have been conducted in 3KL and 3Ps during 1997-1999. In each experiment a portion of the catch is tagged and released immediately and a sample of typically 100-200 cod are measured and tagged in the usual manner, then placed in submersible enclosures (50-75 cod per cage). The enclosure is equipped with a thermograph to record water temperatures every 0.5 hr and returned to the same depth of water at which fish were caught. After a period of 5-10 days the cage is hauled to the surface and examined for dead and moribund fish; fish are also examined for general condition and

tag loss. Healthy tagged fish from the enclosure are released. The proportion that survive is an estimate of τ.

Let M_x be the total number of fish in cage experiment x. We assume that the number of fish that survive in the cage (R_{xc}) is Poisson distributed, with expectation

$$E(R_{xc}) = \tau M_x. \tag{7}$$

Information about τ is also available by comparing time-series of tag-returns for fish that survived cage experiments and fish that were released directly. This is because we can assume that tagging-induced mortality is zero for fish that survive cage experiments. The modification of (6) we use for tag-returns from cage experiments is

$$E(R_{xgti}) = \begin{cases} \mu_{gti} d_{xti}, & \text{if } x \text{ is a cage experiment,} \\ \tau \mu_{gti} d_{xti}, & \text{otherwise.} \end{cases} \tag{8}$$

Inferences about τ are based on both (7) and (8).

An important assumption we have made when considering tagging-induced mortality is that rates of mortality do not differ significantly with the method used to capture the fish. This assumption may not be realistic; for example there is speculation that otter-trawl caught fish may experience higher tagging-induced mortality than fish caught using handlines or traps. We have attempted to address this question in several ways: (1) by holding and tagging otter-trawl caught cod in tanks on board our research vessel for several days, (2) by including trawl-caught fish in our submersible enclosure experiments, and (3) by tagging otter-trawl and handline-caught fish from the same general area and comparing the numbers of recoveries. Although these experiments are ongoing and results have not been subjected to detailed analyses, indications are that survival of tagged cod is high and there is no evidence of major differences in survival between tagged cod caught with otter trawls or handlines.

For example, of 100 cod caught at depths of 130 m with an otter trawl and tagged and retained in tanks on board the research vessel for 5 days, only 3 died and the remainder appeared healthy and were released. Similarly, in submersible enclosure experiments we found no difference in survival between fish trawled at depths of 100 m and those caught with handline at depths of 15-50 m. There was also no difference in survival of tagged and untagged fish that were retained in the enclosures. In addition, two large batches of cod (N=1212 and N=3110) of similar mean length, one caught using an otter trawl at depths of 150-206 m and the other caught in the same general area (inner Placentia Bay) at 15-50 m using handlines, were tagged and released in late April and early May 1998. To date, the percentages reported as recaptured from these two groups are similar, 30.4 and 25.5, suggesting no major difference in tagging mortality between handline-caught and otter-trawl caught cod. With otter trawling there can be large numbers of damaged fish that have to be discarded rather than tagged, particularly when catches are large. We emphasize the importance of only tagging cod that are in excellent condition, irrespective of the method of capture.

5 Results

The first step in our analyses is to estimate reporting rates and tag loss rates. For this we use conditional inference procedures similar to those in Cadigan and Brattey (1999b). We estimate reporting rates for single and double tag-returns separately for each region, with the exception that we estimate combined reporting rates for 3NO and offshore 3PS (denoted as OFF_SH) because of the very small number of returns from 3NO (only 6). The parameter estimates and standard errors are presented in Table 1. To facilitate

Table 1. Estimated reporting rates and tag loss rate for tagging experiments in NAFO Divisions 3KL and subdivision 3Ps during 1997-1999.

Parameter	Estimate	Approx. Std Err	T Ratio	Approx. Prob>|t|
λ^I_{3Ps-PB}	0.650	0.027	24.130	< 0.000
$\lambda^I_{3K-IN} - \lambda^I_{3Ps-PB}$	0.078	0.079	0.983	0.326
$\lambda^I_{3L-INN} - \lambda^I_{3Ps-PB}$	0.185	0.101	1.829	0.067
$\lambda^I_{3L-INS} - \lambda^I_{3Ps-PB}$	0.031	0.100	0.316	0.752
$\lambda^I_{OFF-SH} - \lambda^I_{3Ps-PB}$	-0.015	0.143	0.108	0.914
$\lambda^I_{3Ps-WB} - \lambda^I_{3Ps-PB}$	-0.062	0.068	0.921	0.357
$\lambda^I_{3Pn_4RS} - \lambda^I_{3Ps-PB}$	-0.307	0.092	3.338	0.001
λ^{II}_{3Ps-PB}	0.710	0.032	22.189	< 0.000
$\lambda^{II}_{3K-IN} - \lambda^{II}_{3Ps-PB}$	0.084	0.102	0.825	0.410
$\lambda^{II}_{3L-INN} - \lambda^{II}_{3Ps-PB}$	0.125	0.137	0.913	0.361
$\lambda^{II}_{3L-INS} - \lambda^{II}_{3Ps-PB}$	0.041	0.117	0.346	0.729
$\lambda^{II}_{OFF-SH} - \lambda^{II}_{3Ps-PB}$	-0.075	0.213	0.353	0.724
$\lambda^{II}_{3Ps-WB} - \lambda^{II}_{3Ps-PB}$	-0.087	0.081	1.075	0.282
$\lambda^{II}_{3Pn-4RS} - \lambda^{II}_{3Ps-PB}$	-0.167	0.136	1.232	0.218
b	0.028	0.006	4.632	< 0.000
c	0.010	0.004	2.338	0.019

comparisons of the differences in reporting rates among regions we actually estimated the reporting rates for 3Ps_PB, and the differences in reporting rates between 3Ps_PB and the other regions. Reporting rates in the other regions can be obtained by adding the difference estimates to the estimated reporting rate in 3Ps_PB, and these are shown in Table 2.

Note that in preliminary analyses λ^{II}'s in 3L_INN and OFF_SH were estimated to be less than λ^I's. We feel this is implausible, so the parameter space was constrained so that $\lambda^{II} \geq \lambda^I$. Inferences in Tables 1 and 2 are based on this constraint. The results indicate that the reporting rates are somewhat higher in 3KL than in 3Ps. The reporting rates

Table 2. Reporting rate estimates

Region	Type I	Type II
3PS-PB	0.650	0.710
3K-IN	0.728	0.794
3L-INN	0.835	0.835
3L-INS	0.682	0.750
OFF-SH	0.635	0.635
3PS-WB	0.588	0.623
3PN-4RS	0.343	0.543

in 3Pn and 4RS are significantly lower. This finding is consistent other mark-recapture studies which have found that reporting rates tend to diminish with distance from the release sites (Henny and Burnham 1976; Conroy and Blandin 1984).

The estimated parameters of the tag loss function $\phi(\cdot)$ are presented at the bottom of Table 1. The estimated tag loss function is shown in Figure 2. The results suggest that 5%

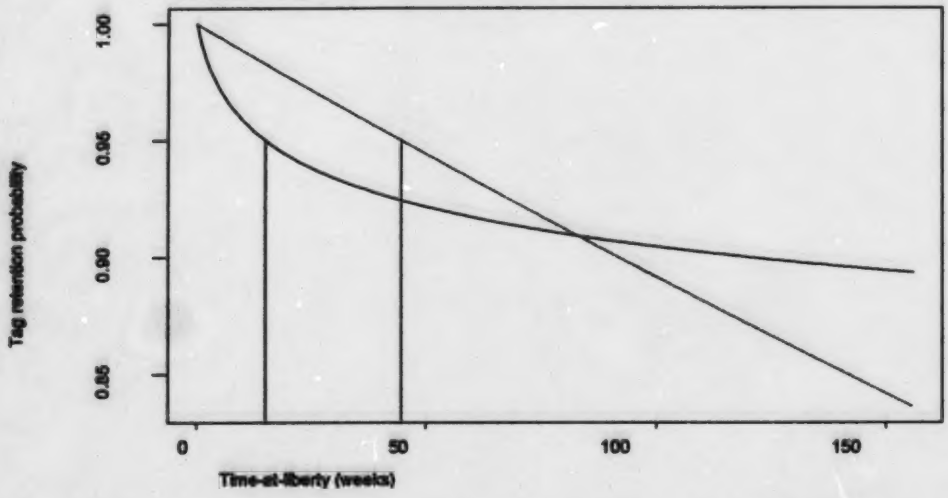


Figure 2: Tag retention estimates for tagging experiments in 3KL and 3Ps during 1997-1999. The solid line is for the 2 parameter model we recommend using, and the dotted line is for the traditional proportional loss model. The vertical lines mark the 95% tag retention percentile.

of fish have lost their tag by 16 weeks, but tag loss diminishes rapidly after that; for example, at 3 years over 90% of fish still retain their tag. The more traditional proportional loss model suggests considerably different results. The 2-parameter model offers a substantial improvement in fit compared to the proportional loss model (p-value <0.0001). Other

unreported analyses we have conducted suggest that further improvement in fit beyond that provided by the 2-parameter model will be marginal. These results will be presented elsewhere.

We also tested for annual differences in reporting rates, although not with geographic interactions. We estimated a common λ^I and λ^{II} for all regions, but separately for 1997, 1998, and 1999. We did not include regional interactions because of the small number of tag-returns in most regions in 1997 and 1998. The combined estimates for 1999 are $\hat{\lambda}^I = 0.668$ and $\hat{\lambda}^{II} = 0.724$. The difference estimates for 1997 and 1998 are 0.0726 and -0.0366 for type I tags, and 0.0671 and -0.065 for type II tags. These difference estimates were not significantly different (i.e. all p-values>0.2). Our conclusion from this exercise is that overall there does not seem to be significant inter-annual variations in reporting rates. We acknowledge that our test will be heavily weighted towards reporting rate variations in Placentia Bay because most of the tag-returns come from this region.

The next step is to estimate the length of all tagged fish given their length-at-release and time-at-liberty. The growth model we use for this is described in Cadigan and Brattey (2000). The parameter estimates for the model are presented in Table 11 in Cadigan and Brattey (2000), and some example predicted growth increments are shown in Figure 17 in that paper.

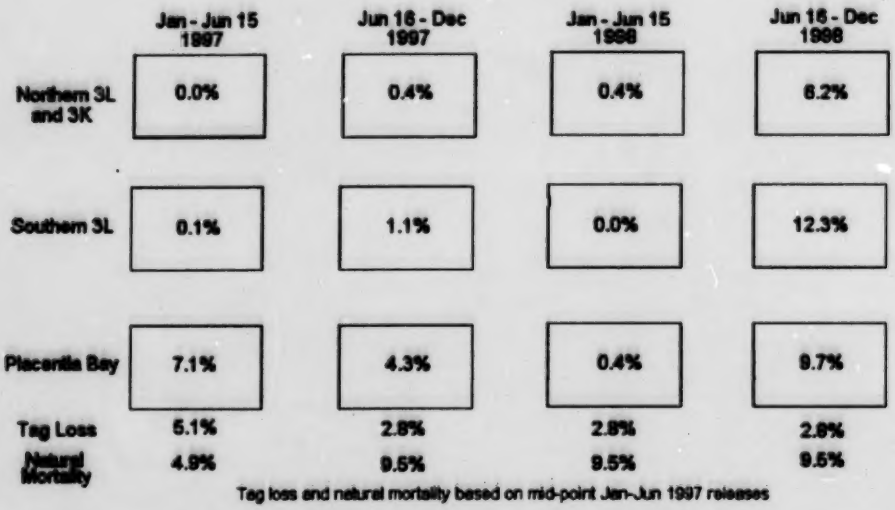
We present two analyses to estimate exploitation rates. The first analysis (**Run1**) assumes no tagging-induced mortality and constant selectivity. This model is most similar to that considered in the last assessment of this stock. We present this analysis because it is useful to compare our present estimates of exploitation in 1997 and 1998 with those presented in the last assessment of 3KL cod. If there are major discrepancies then the model formulation in both assessments must be investigated further. The second analysis (**Run2**) we present involves estimating gear selectivity and tagging-induced mortality.

5.1 Run1: Comparison

This run is presented so that the estimators we propose can be compared with the tagging-based estimators of exploitation and migration rates last considered for this stock (see Cadigan and Brattey, 1999a). The methods in Cadigan and Brattey (1999a) did not include gear selectivity. To facilitate comparisons we constrain relative selectivity to be 1 in this run, which was an implicit assumption in Cadigan and Brattey (1999a). Likewise, Cadigan and Brattey (1999a) assumed no short-term tagging mortality, and we do the same in this run. Over 500 parameters are estimated, and it is not useful to present them all. We compute approximate semi-annual exploitation rates by summing the weekly exploitation estimates over gears and weeks, for the same semi-annual intervals used in Cadigan and Brattey (1999a); that is, for weeks 1-24 and 24-52, each year. The sum is for a specific length - which length does not matter because exploitation is assumed to be constant for all lengths. These results are presented in Table 3, and can be compared with those of Figure 7 in Cadigan and Brattey (1999a). This figure is reproduced below for convenience.

Table 3. Approximate semi-annual percentage exploitation estimates for the constant selectivity model.

	1997		1998		1999	
Region	→Jun 15	Jun 16→	→Jun 15	Jun 16→	→Jun 15	Jun 16→
3K-IN	-	-	1.9	12.2	1.1	40.6
3L-INN	-	0.4	0.8	4.1	0.8	8.7
3L-INS	-	2.3	0.5	2.2	0	1.9
3PS-PB	12.9	6.2	0.6	12.7	1.9	20.8
3Ps-OF +3NO	-	-	0.4	1.5	0.6	1.1
3PS-WB	-	-	0.6	12.7	3.8	4.0



Exploitation rate estimates in Placentia Bay (3Psc) and the inshore regions of 3KL, from Cadigan and Brattey (1999a).

There are some substantial discrepancies between exploitation estimates. For example, the estimate of exploitation in 3Ps_PB for Jan-Jun 15, 1997 from the 1999 assessment was 7.1%, whereas in Table 3 it is almost 13%. The discrepancy is likely related to the assumptions about the exploitation of tagged-cod within the same time-cell of release. Cadigan and Brattey (1999a) assumed that these fish were fully exploited by the fishery. If the fishery actually occurred prior to the release of tags in a time cell then this would give the appearance of low exploitation. In hindsight the better approach would have been to base exploitation in a time cell t only on releases in previous cells, and not on releases in time cell t. For the coarse level of temporal aggregation considered in Cadigan and Brattey (1999a) this would have reduced the precision of inferences considerably. We feel

that we have adopted a better procedure in this paper, which is to temporally aggregated tag-returns only at a minimal level, thereby reducing the above problem. For example, on a weekly scale only 41 out of 4007 tags were returned within the same week of release.

Another major discrepancy is the exploitation estimate in Jun 16-Dec in 1998 in 3L_INS. In the 1999 assessment this estimate was 12.3%, whereas in Table 3 the estimate is 2.2%. This discrepancy is due to the assumption of no migration in our current analysis. A substantial number of tags are returned from fish released in 3L_INS but caught in 3Ps_PB. Also, a substantial number of tags are returned from fish released in 3Ps_PB but caught in 3L_INS. This indicates considerable mixing between these two regions. The analyses in Cadigan and Brattey (1999a) attempted to accommodate for this mixing, with the result that the size of the 1998 tagged population in 3L_INS in their paper (e.g. see Figure 9 in Cadigan and Brattey, 1999a) is much smaller than the population we estimate here when no migration is assumed to occur. This assumption is fallacious, and our estimates of exploitation rates for 3L_INS are much too low.

This run has indicated problems with both the tagging model used in Cadigan and Brattey (1999a) and the model we use here. The complications caused by migration between regions and our inability to accommodate for this in our model must be kept in mind when interpreting the next analysis.

5.2 Run2: Realistic

Two criticisms of the analyses in Cadigan and Brattey (1999a) are that they did not consider the effect of a length selective fishery, and they did not allow for short-term tagging-induced mortality in their model. Also, their method for dealing with tag-returns in the same time period of release led to under-estimation of exploitation rates in some circumstances. In this run we model both the length selectivity of fishing gears and tagging-induced mortality. The finer temporal aggregation we use here also greatly reduces the problem of modeling tag-returns from the same time period of release. We do not attempt to estimate migration rates however. This means that exploitation rate estimates are based only on tags returned from the same region they were released in. For the eight regions we consider in our model, 25% of the tags were returned outside the regions they were released in. This includes tagged fish caught in 3NO and 3Pn+4RS. Our exploitation rate estimators exclude exploitation of tagged fish released in 3Ps but caught in 3Pn+4RS, 3NO, and 3L. Likewise, our analyses exclude exploitation of fish tagged in 3KL but caught in 3Ps.

Estimated selectivity curves are presented in Figures 3-6. We use a parametric model for selectivity,

$$s_l = s(l) = \exp(\beta_1 l + \beta_2 l^2).$$

We estimate β_1 and β_2 using the conditional multinomial likelihood based on (5). Estimates are obtained using maximum likelihood. Estimates of s_l are re-scaled so that $\max_l s_l = 1$. Note that (5) is invariant to scalar transformations of s_l, and scaling selectivities can be done after estimation, rather than using constrained optimization. Where

possible we have estimated selectivities separately for each of the six regions where tagged fish have been released in, and for each year and gear type; however, we decided to combine estimates over years and regions for many of these cells because of small sample sizes. The region×year combinations are indicated in Figures 3-6.

The gillnet selectivity curves shown in Figure 3 look intuitively reasonable, and are consistent with the shape of gillnet selectivity curves estimated by Myers and Hoenig (1997). In 1998 and 1999 there were a large number of tag-returns from 3Ps_PB from which gillnet selectivities could be estimated. In Placentia Bay gillnet selectivity appears to have shifted towards slightly larger fish in 1999 compared to 1998, although this difference may not be statistically significant. The fully selected lengths for gillnets in the three regions in 3KL appear lower than in 3PS_PB or 3Ps_WB, and this might reflect that the average length of fish in 3KL is lower than in 3Ps. The selectivity curve for gillnets in the offshore of 3Ps is based on very few tag-returns (6), and is poorly estimated. Fortunately the offshore gillnet catch accounts for very little of the total exploitation in this region, and imprecise estimates of gillnet selectivity will not have much consequence in terms of estimating total exploitation.

The selectivity estimates for handlines in Figure 4 are also usually based on few tag-returns. The estimated selectivities in regions with sample sizes ≥ 30 (3K_IN, 3L_INN, 3Ps_PB) are fairly consistent with the historic estimates given in Myers and Hoenig (1997). Estimates of handline selectivities in the other regions in Figure 4 may not be reasonable, but this is not of much consequence because handlines account for little of the total exploitation in these regions.

The estimated selectivity curve for linetrawls in 3Ps_PB during 1997-1999 (see Figure 5) is also fairly consistent in shape with the historic estimates presented in Myers and Hoenig (1997). The ottertrawl selectivity curve in Figure 5, although based on a fairly small sample size, is domed-shaped. The trap selectivity function for 3PS_PB in Figure 6 also seems reasonable in that it suggests that traps select relatively small fish, which is consistent with the general understanding of this type of gear. The selectivity estimates for the "unknown" gear type resemble the gillnet selectivity curves. This is reasonable because in the 3Ps and 3KL commercial fisheries, gillnets are used much more frequently than the other gear types, and it is likely that the majority of "unknown" gears were actually gillnets.

The estimates of gear selectivities are combined using (6) for estimating weekly exploitation rates for each gear type and region (e.g. μ_{gti}'s), and short-term tagging mortality ($1-\tau$; see eqn. 7 and eqn. 8). The estimate of τ is 0.86, which suggests that on average 14% of tagged fish die due to tagging. Each μ_{gti} (see eqn. 4) is the maximum (over length) exploitation rate for each gear type and region. Weekly estimates of μ_{gti} are plotted in Figures 7-11. In these figures the exploitation rates are stacked by gear type for each week; however, the length at which exploitation is maximum differs for each gear type, so these figures do not contain the maximum exploitation rates for fish of specific lengths. These figures are useful for examining the weekly gear composition of the fishery.

In 1997 no fish were tagged in 3K_IN, 3Ps_OFF, or 3Ps_WB so the μ_{gti}'s could not be estimated. The exploitation rates in 3L appear very low (see Figure 7) because

there was no commercial quota for cod in this region in 1997. Tag-returns came only from the sentinel, by-catch, and recreational fisheries. There was a 10 000 t quota for cod in 3Ps in 1997, and approximately 6 000 t was landed from 3Ps_PB. This is the reason for the relatively high exploitation estimates in 3Ps_PB. The majority of fish with tags were reported to have been caught with gillnets and codtraps. The three pulses of exploitation evident in the bottom panel of Figure 7 (May 22-28, June 29-July 5, October 5-11) correspond well to the dates of the fishery openings in 3Ps in 1997. Hence, the estimates in Figure 7 seem reasonable.

In 1998 there was a 4 000 tonne quota for cod in 3KL which resulted in higher estimates of μ_{gti} in some weeks (see Figure 8) compared to 1997, particularly in 3K. No one gear type dominated 3KL exploitation in 1998. There was a 20 000 tonne quota for cod in 3Ps in 1998. The bulk of total exploitation involved gillnets (see Figure 9). The fishery in 3Ps_PB exploited cod throughout most of the fishing season, but particularly in the first part of July, and October-mid November.

In 1999 there was a 9 000 tonne quota for cod in 3KL, and the majority of the exploitation involved gillnets (see Figure 10). Commercial fishing was closed during August, which is the reason for the low exploitation rate estimates for this month in Figure 10. In Figure 11 we see again that the bulk of the 1999 quota of 30 000 tonnes in 3Ps was taken using gillnets. A substantial portion of the total exploitation occurred in the fall in 3Ps_PB.

The particular concern of this paper is the total exploitation rates in 3KL during 1999, and also the 1999 biomass of cod. To estimate total weekly exploitation rates we combined estimates of μ_{gtti} using estimates of the weekly length distribution of the commercial catch for each region and gear type. The method for combining the μ_{gtti}'s is outlined in **Section 3.1**. The commercial catch length distributions were estimated from port sampling data. The μ_{gtti}'s were obtained by multiplying the estimates of μ_{gti} and s_{gli} (see eqn. 6). The weekly exploitation estimates for 3K_IN, 3L_INN, and 3L_INS are presented in the middle row of panels in Figure 12. The total catch is presented in the top row of the panels. Recall that the exploitation estimates are not computed using the commercial catch information, but there is generally good agreement between the peaks of the tagging-based exploitation rate estimates and the reported landings. We expect this if the abundances of cod in these areas does not vary substantially within a year.

Weekly biomass estimates are presented in the bottom row of Figure 12. There is considerable weekly variation in the abundance estimates, the level of which is beyond any expected weekly variations in stock abundance in these three regions. The highest variability seems to be associated with periods where the commercial catch is small. Some of this variability may be the direct consequence of variability in our estimates of weekly exploitation. This is compounded by:

1. errors in the week fishermen report that a tagged fish was captured,
2. errors in the reported capture region, and
3. errors in the weekly reported landings by the commercial fishery.

We do not directly accommodate these uncertainties into our stochastic model for tag-recaptures. We simply smooth the weekly biomass estimates (shown as solid lines in the bottom panels of Figure 12) using the Splus smoother "supsmu", with a 10% span.

To further simply the tagging estimates of stock size we decided to combine information in each region for the two time periods in which most of the commercial fishing in 1999 took place: July, and September 5 to October 10. We refer to these two time periods as pulse 1 and pulse 2. The total catch, exploitation, and biomass estimates are presented in Table 4. We first note **emphatically** that the exploitation estimates for the two time

Table 4. Exploitation and biomass estimates in three inshore regions of 3KL during 1999. Fishing pulse 1:July. Fishing pulse 2: Sept. 5 - Oct. 10.

Region	Pulse	Total catch (tonnes)	Exploitation rate (%)	Biomass (10^3 tonnes)
3K-IN	1	1742.06	19.39	8.98
	2	1531.87	13.49	11.35
3L-INN	1	1140.32	2.33	48.96
	2	1629.13	3.85	42.35
3L-INS	1	724.49	0.43	166.90
	2	791.54	0.60	131.45

periods in 3L_INS are under-estimates, and we suspect the degree of under-estimation is considerable. This is because there appears to be substantial movement of fish between 3Ps_PB and 3L_INS; for example, 66% of fish tagged and released in 3L_INS during 1997-1999 were recaptured in 3Ps_PB also during 1997-1999. This suggests that the estimated size of the tagged population in 3L_INS, which is used to estimate exploitation rates, could be much too high. This would lead to underestimation of the exploitation rate.

Remark 2 *We suggest that the estimates of population biomass for 3L_INS are unreliable.*

These estimates are presented for scientific archival purposes only.

The biomass estimates for 3K_IN and 3L_INN appear reasonable. For example, if both regions together comprise bound a local stock then

Remark 3 *the estimates suggest that the biomass of fish in 3K_IN+3L_INN during July of 1999 was 57.94 thousand tonnes. During September 5 to October 10 the biomass decreased to 53.70 thousand tonnes.*

Note that the catch during the July fishing pulse was 2.88 thousand tonnes, and if this is added to 1/6th of natural mortality (annual $m = 0.2$) then we would predict the biomass to decrease between the two pulses by 4.78 thousand tonnes. This is in close agreement

with the estimated decrease of 4.24 thousand tonnes between the two nearly independent biomass estimates. Note however that there are considerable uncertainties in the biomass estimates that we have not attempted to quantify. We do not propose that the estimates are perfect, but we merely suggest that at least the estimates are not obviously incorrect.

We further explore the validity of the estimates by assessing the validity of the model fit to the data. We use residual plots for this purpose. Residual time-series plots for all experiments in each region are presented in Figures 13-18. The plots are stratified by release year in each panel. These plots are presented to reveal potential "gross" model mis-specifications. Residual plots for each experiment are presented latter that are useful for detecting mis-specifications at a finer level, although such mis-specifications will tend to be less influential than "gross" mis-specifications.

In the top and middle panels of Figure 13 we see that overall there is a trend to over-predict (i.e. negative residual) tag-returns in 1999 from 1997 and 1998 releases. This suggests that the exploitation for these experiments is over-estimated or that the number of tagged fish in the population from these experiments is over-estimated. The skewness in the residuals is to be expected. The predicted probability of getting a tag-return from a specific experiment in any week is usually very low. Corresponding to this, in most weeks in which at least some exploitation of cod occurs in 3K_IN we do not get tag-returns from most experiments, and these zero returns result in many small negative residuals. The relatively rare event of a tag-return results in a large positive residual, which is to be expected with this type of data.

Similar residual patterns are present for tag-returns from 3L_INN (Figure 14) and 3L_INS (Figure 15); that is, the tag-return model tends to over-predict the number of 1999 returns from 1997 and 1998 experiments. Note that in 3L_INN there were no 1998 experiments which is why Figure 14 has only two panels. Also note in the bottom panel of Figure 15 that the skewness in the residuals is pronounced. This could be caused by incomplete mixing of the tagged fish from all experiments, and spatial variations in exploitation. In this case the fishery in any week might be spatially restricted and exploit a particular experiment more than others. This would result in a relatively large residual for that experiment because the model predicts tag-returns using the weekly "average" exploitation for the whole region, which might still be low even though in a restricted area local exploitation is high. The other consequence is many small negative residuals from experiments that were not exploited (i.e. zero returns). We will explore this in more detail below.

The 3Ps tag-return residuals (Figures 16-18) do not show the same degree of model mis-specification in which we over-predict the number of 1999 returns from 1997 and 1998 experiments, although this is still evident for 3Ps_PB (see Figure 16).

Time series of average weekly residuals for each experiment are shown in Figures 19-27. Residuals are produced for all the gear types used each week. In Figures 19-27 we present only the average of these residuals. We also present the annual average residual to aid in assessing the tendency of our model to under- or over-predict tag-returns each year. We focus our attention on the 1999 residuals for 3KL tagging experiments, because this is the part of the tagging data that is most relevant to the 1999 assessment of cod in 3KL.

As we have already mentioned the residuals for 1999 returns from 1997 and 1998 releases tend to be negative which indicates that we observed fewer tag-returns than the model predicted. This is not always the case however; for example, in 3L_INN the average of the 1999 residuals are nearly zero for experiments 9710 and 9716. These tagging experiments occurred in 1997. Otherwise we find no systematic patterns in the residuals. There appears to be heterogeneity in the exploitation rates for individual experiments, as we also mentioned previously, but this heterogeneity seems to be of a random nature. This does not indicate any serious mis-specifications of our tagging model beyond the problem that our model does not accommodate movements of fish between geographic regions.

6 Discussion and Conclusions

Our analysis of the 1997-1999 tag-return information for NAFO Divisions 3L and 3K indicates exploitation from the fishery in July of 1999 in the inshore regions of 3K was high (estimated to be 19.4%), but lower in 3L north of Conception Bay (2.3%). We were unable to produce a reliable estimate of the exploitation rate for the southern part of 3L (south of Conception Bay, inclusive). During the period September 5 to October 10 the exploitation rate in the inshore regions of 3K was estimated to be 13.5%, and the exploitation rate in the northern part of 3L was estimated to be 3.9%. Based on these exploitation rate estimates and the reported commercial landings during these time periods, we estimated the combined biomass in inshore 3K plus northern 3L to be 58 000 tonnes in July of 1999, and 54 000 tonnes in September 5 to October 10.

Our tagging model is deficient in that we were unable to accommodate for migration of fish. The result of this is that 25% of the tag-returns in 4R, 4S, 3Pn, 3Ps, 3NO, 3K, and 3L during 1997-1999 could not be explained by our model; however, most of the problems are with mixing between 3Ps and 3Pn+4RS and southern 3L. We feel our exploitation and biomass estimates for the northern part of 3L and 3K are reasonable. There is still a problem even with this part of the data; that is, the tag-returns from the small number of experiments conducted in 3K+3L in 1997 and 1998 were lower than our model predicted. This could be caused by incorrect modeling of fish movements, natural mortality, or exploitation rates. More investigation into this problem is required.

We have taken the approach of analyzing the tag-returns at the smallest level of aggregation that seems reasonable. This improves on the approach taken in Cadigan and Brattey (1999a) because we are able to use tag-returns a week after their release. Cadigan and Brattey (1999a) used a coarse bi-year time scale and incorrectly modeled tag-returns in the same time period they were released in. We have also not pooled tagging experiments, which is different than Cadigan and Brattey (1999a). The advantage of this is that there is contextual information (i.e. fine scale spatial information, etc.) associated with each experiment, and this information can be used when assessing model fit at the disaggregated level we have taken. For example, in preliminary analyses of the tagging data it was discovered that recaptures from three tagging experiments were included in the data-base that should not have been. If we had just aggregated recaptures like Cadigan

and Brattey (1999a) then we would not have detected these experiments in the model fit diagnostics. Our current approach also includes the length-selectivity of the cod fisheries in 3KL, as well as cod growth. The disadvantage of our approach is that it results in a complex estimation problem, and we could not estimate migration rates like in Cadigan and Brattey (1999a). We hope to this in the future.

References

[1] Brattey, J., G. L., Lawson, and G. A. Rose. 1999. Seasonal migration patterns of Atlantic cod (*Gadus morhua*) in Subdivision 3Ps based on tagging experiments during 1997-98. CSAS Res. Doc. 99/37.

[2] Brattey, J. 2000. Stock structure and seasonal movements of Atlantic cod (*Gadus morhua*)in NAFO Divs. 3KL inferred from recent tagging experiments. CSAS Res. Doc. 2000/084.

[3] Cadigan, N. G., and J. Brattey. 1999a. Estimation of coarse exploitation and migration rates of cod in 3Psc and 3KL during 1997 and 1998 based on tagging experiments. CSAS Res. Doc. 99/38.

[4] Cadigan, N. G., and J. Brattey. 1999b. Tag loss and reporting rates for 1997 and 1998 cod tagging experiments in 3Psc and 3KL. CSAS Res. Doc. 99/65.

[5] Cadigan, N. G., and J. Brattey. 2000. Estimation of cod (*Gadus Morhua*) growth in NAFO Subdiv. 3Ps and Divs. 3KL in 1997-1999 from tagging experiments. CSAS Res. Doc. 2000/074.

[6] Conroy, M. J., and W. W. Blandin. 1984. Geographic and temporal differences in band reporting rate for American black ducks. J. Wildl. Managmt. 48: 23-36.

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[9] Myers, R. A. and J. M. Hoenig. 1997. Direct estimates of gear selectivity from multiple tagging experiments. Can. J. Fish. Aquat. Sci. 54:1-9.

7 Appendix: Figures

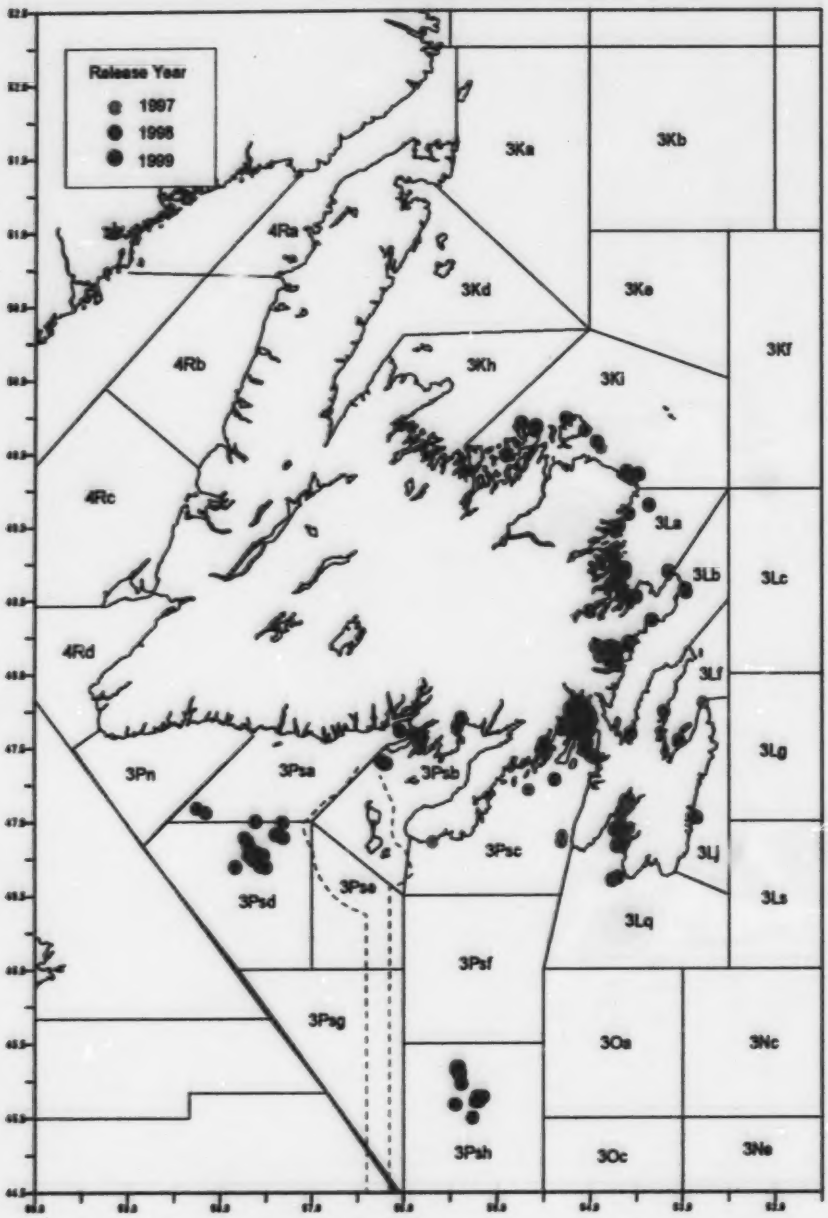

Figure 1: Map of Newfoundland showing the locations of tagging experiments during 1997-1999. NAFO unit areas are delineated with solid lines. The dashed line marks the boundary of the French economic zone.

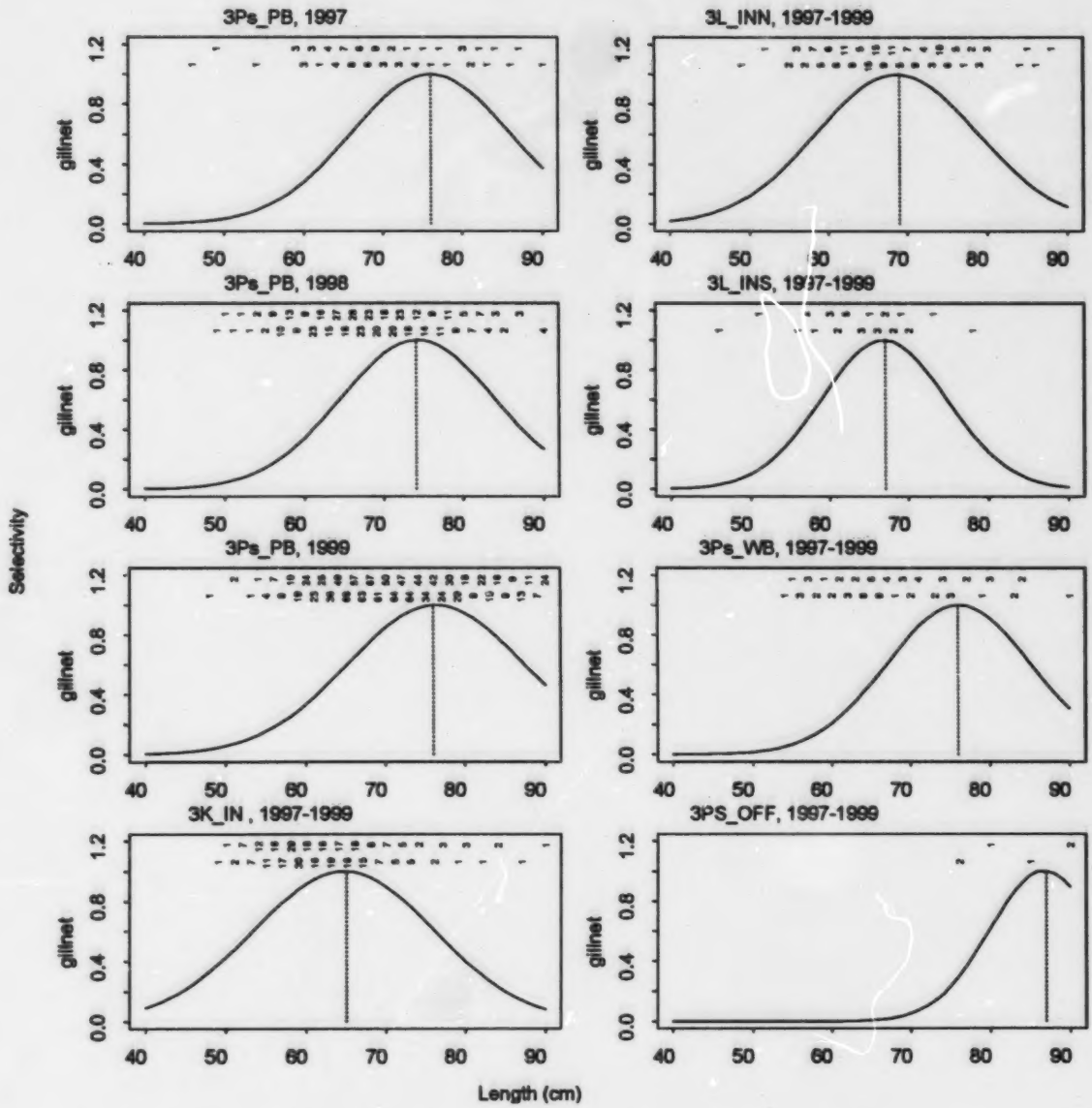

Figure 3: Gear selectivity in 3Ps and 3KL during 1997-1999. The numbers along the top of each panel are the number of tags returned at each length. The vertical line marks the length at maximum selectivity.

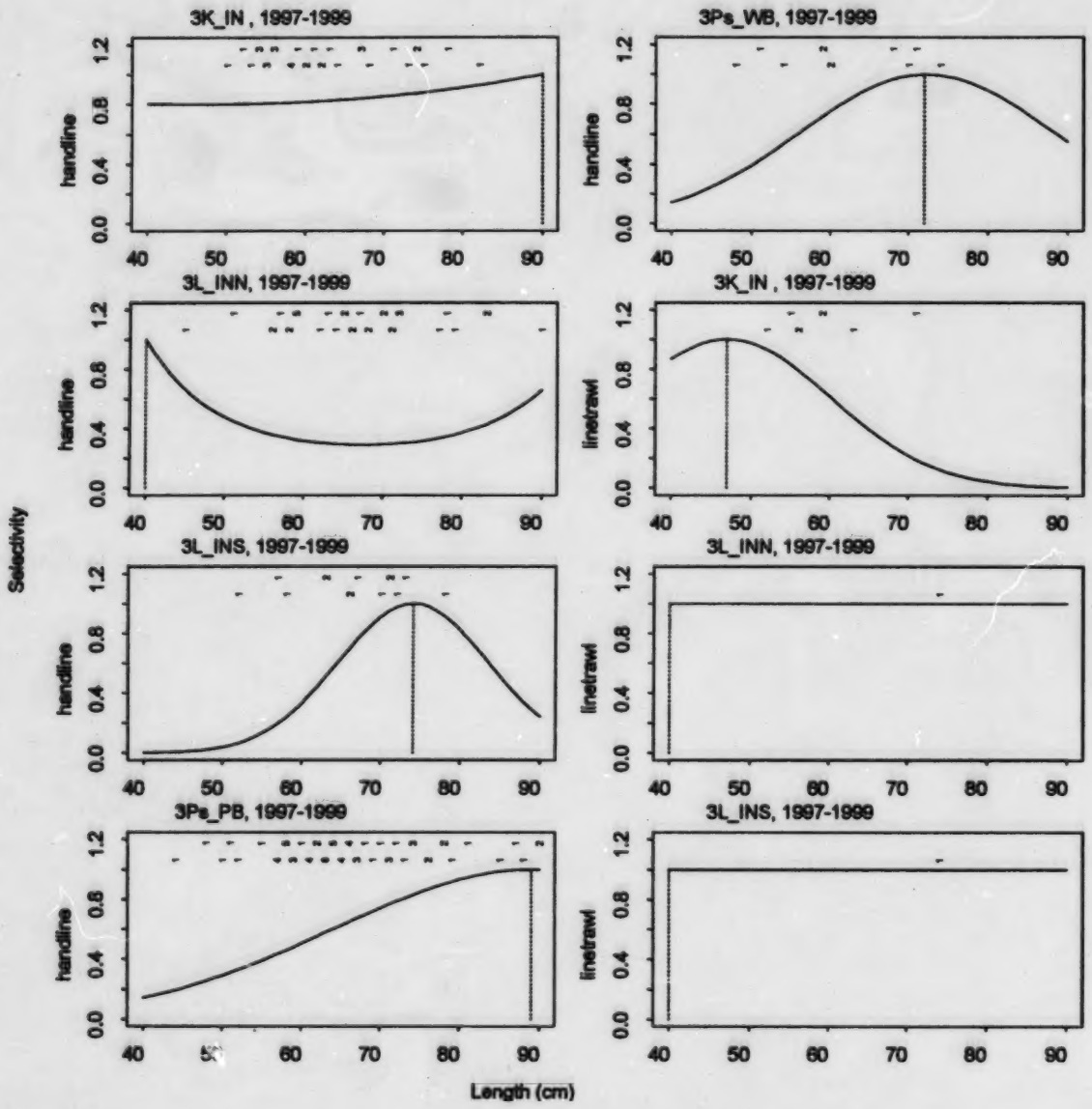

Figure 4: Gear selectivity in 3Ps and 3KL during 1997-1999. The numbers along the top of each panel are the number of tags returned at each length. The vertical line marks the length at maximum selectivity.

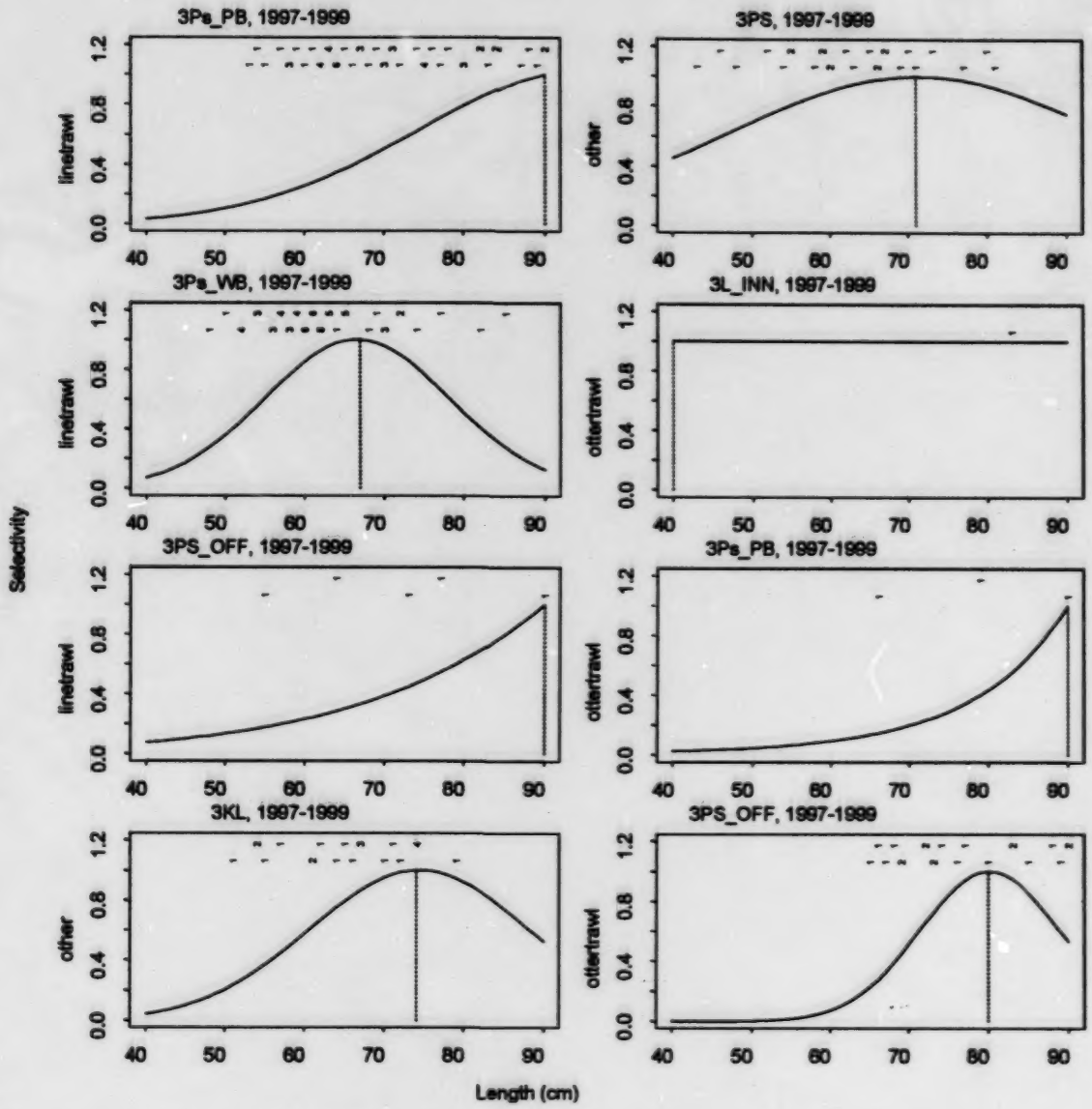

Figure 5: Gear selectivity in 3Ps and 3KL during 1997-1999. The numbers along the top of each panel are the number of tags returned at each length. The vertical line marks the length at maximum selectivity.

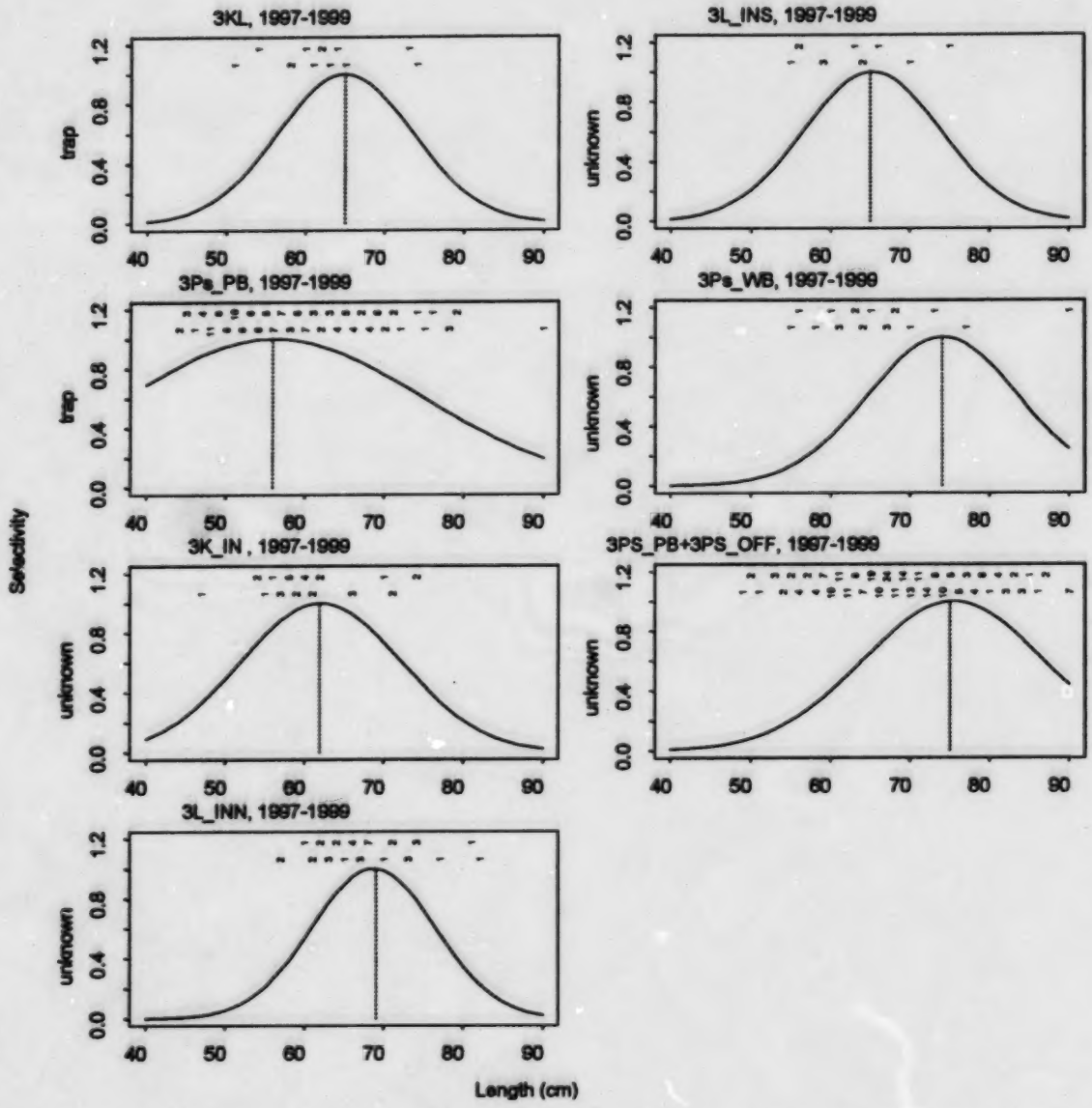

Figure 6: Gear selectivity in 3Ps and 3KL during 1997-1999. The numbers along the top of each panel are the number of tags returned at each length. The vertical line marks the length at maximum selectivity.

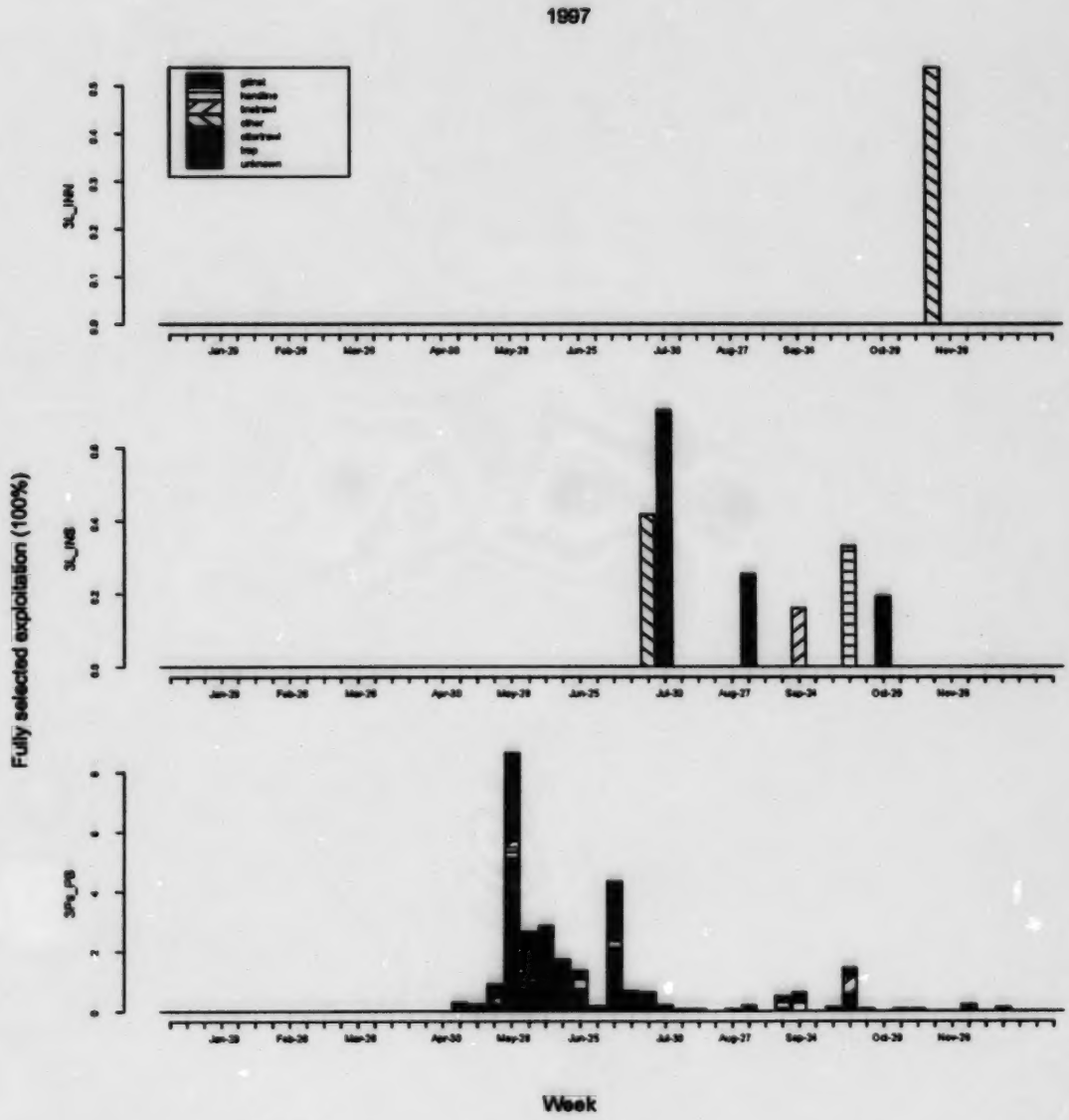

Figure 7: Maximum exploitation for each gear. Each panel represents a geographic region. The time axis is labelled with the last week mid-point in each month.

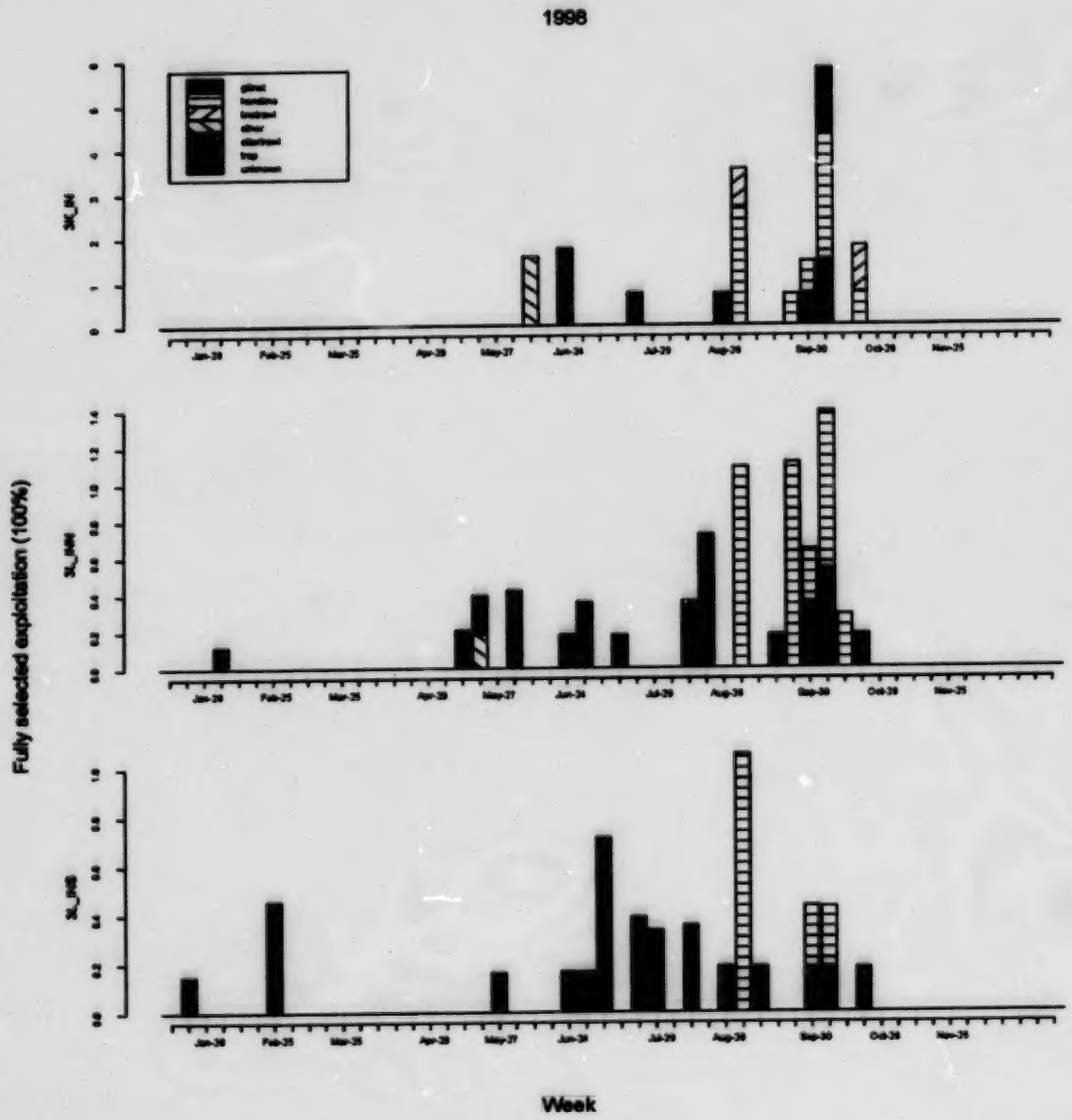

Figure 8: Maximum exploitation for each gear. Each panel represents a geographic region. The time axis is labelled with the last week mid-point in each month.

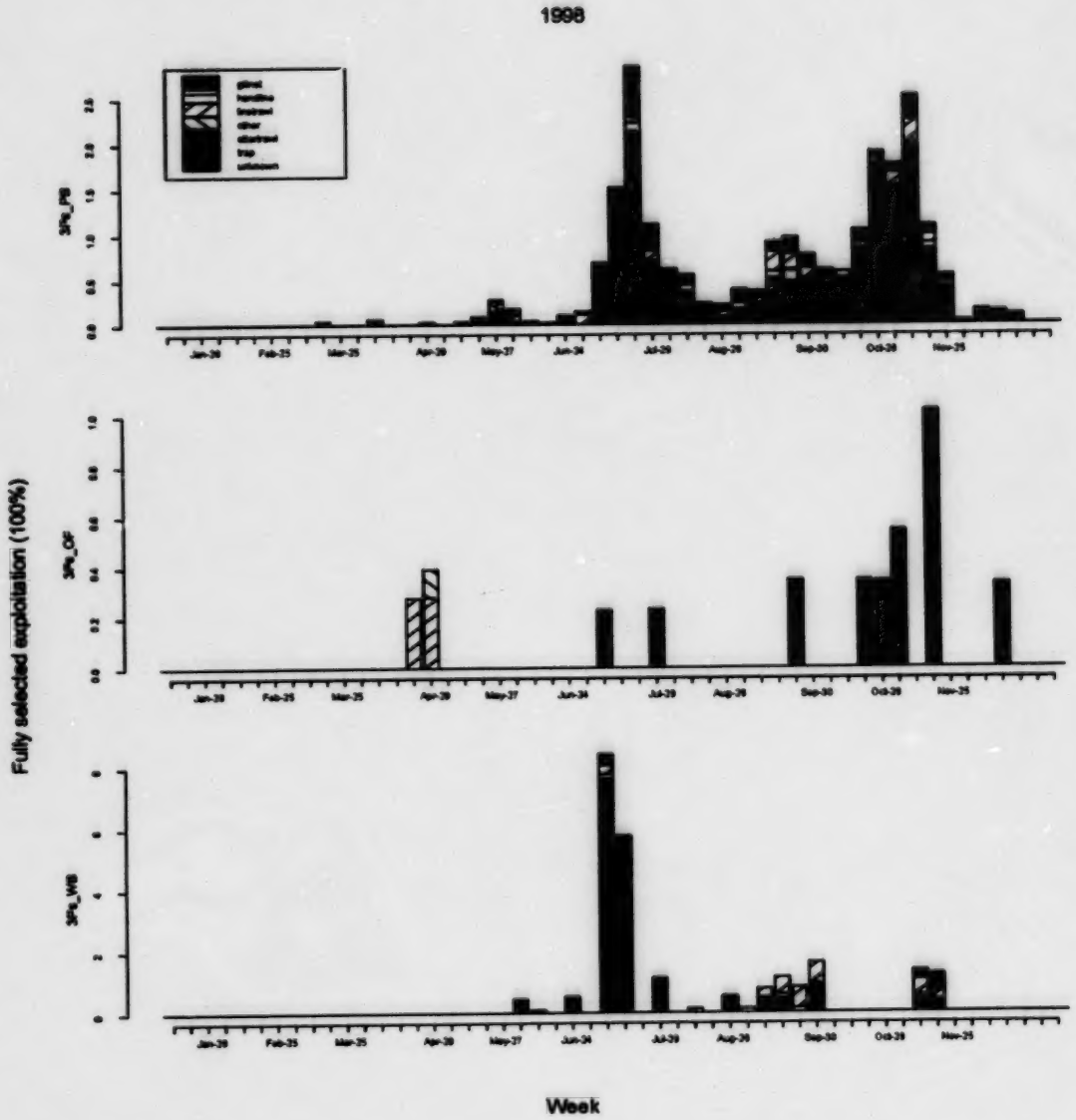

Figure 9: Maximum exploitation for each gear. Each panel represents a geographic region. The time axis is labelled with the last week mid-point in each month.

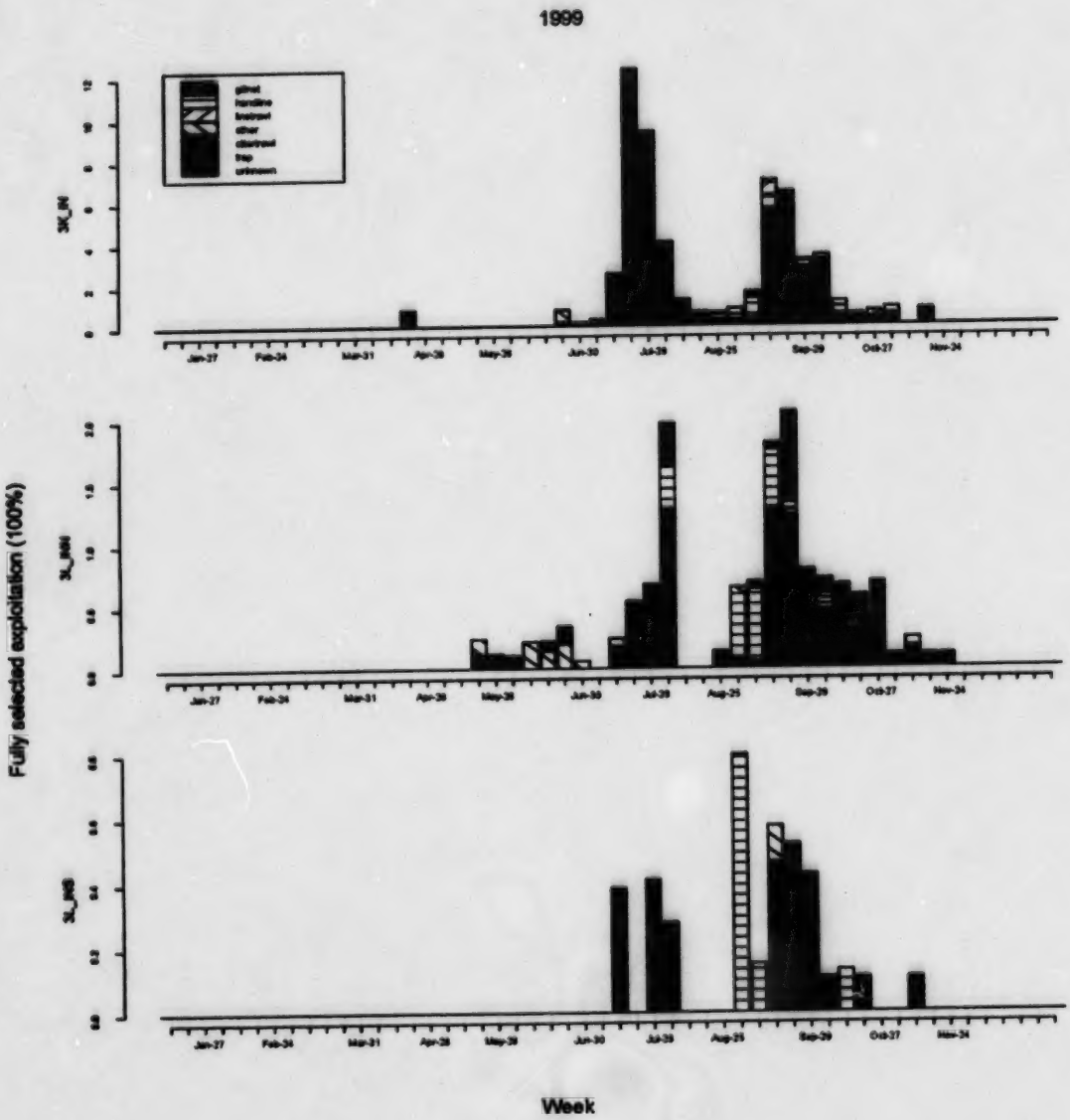

Figure 10: Maximum exploitation for each gear. Each panel represents a geographic region. The time axis is labelled with the last week mid-point in each month.

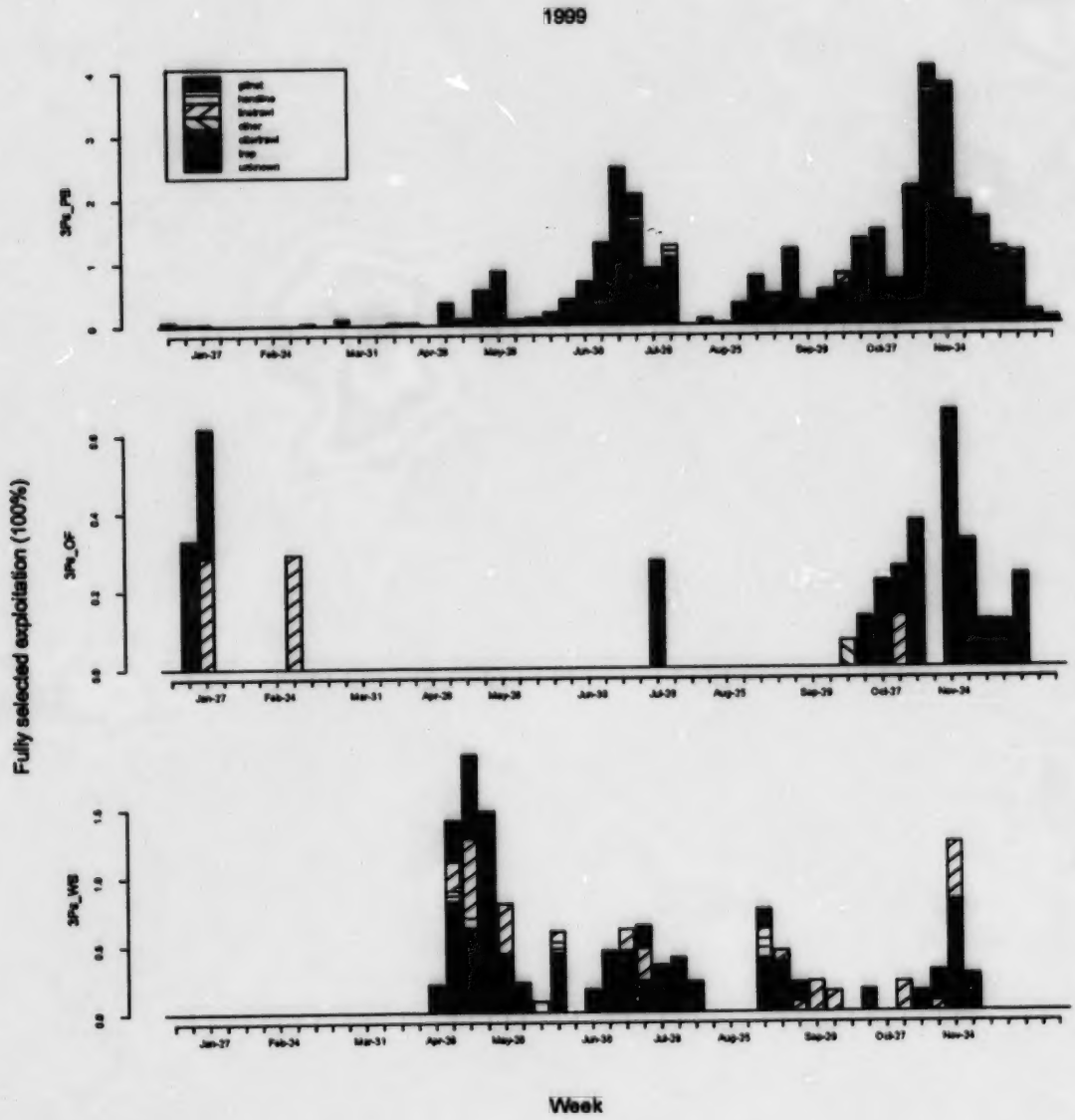

Figure 11: Maximum exploitation for each gear. Each panel represents a geographic region. The time axis is labelled with the last week mid-point in each month.

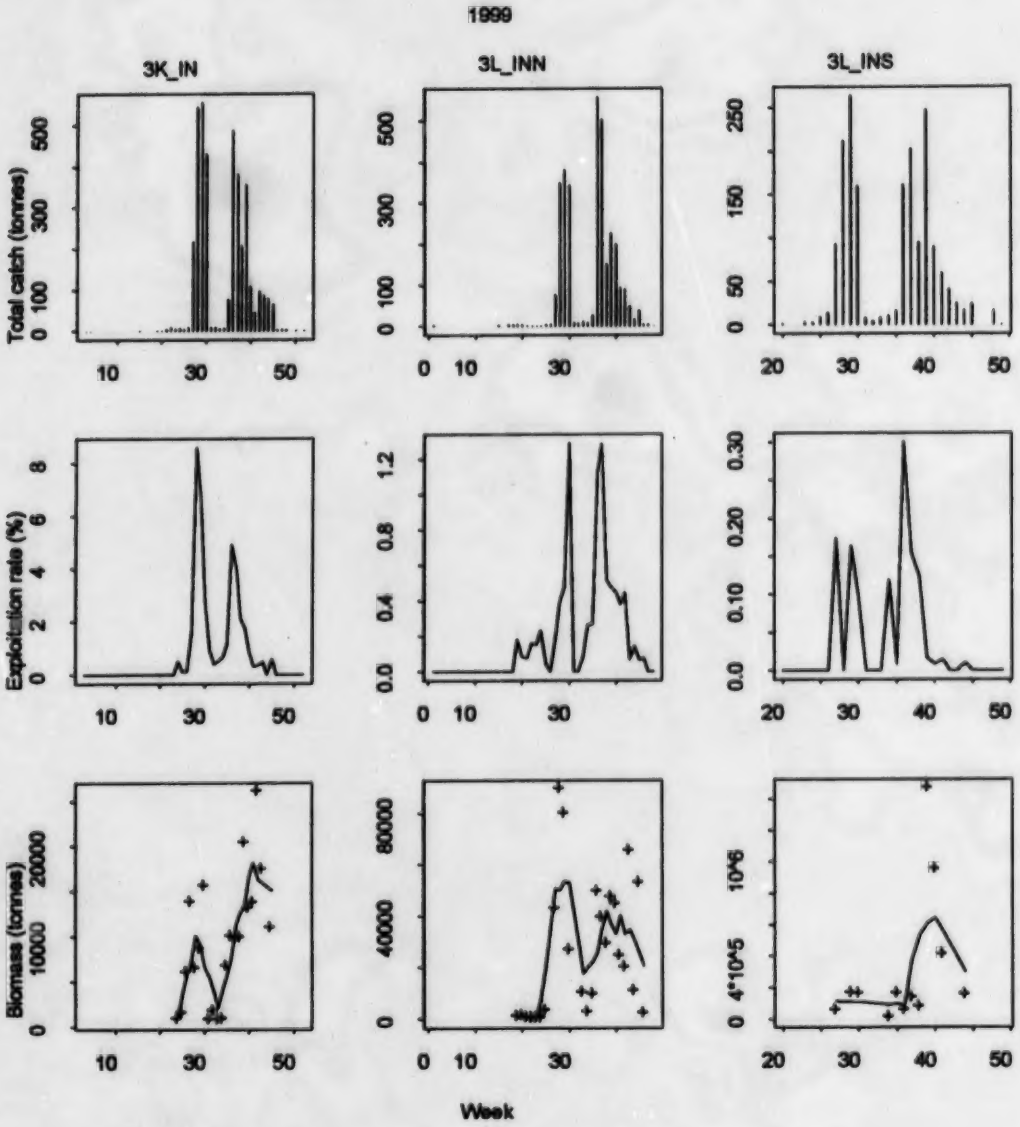

Figure 12: Weekly estimates of total exploitation rates and estimates of biomass in 3KL. The top row of panels give weekly landings in 3K_IN, 3L_INN, and 3L_INS. The middle panels give the exploitation rates for each week. These rates are connected with a solid line. The bottom row of panels give the weekly biomass estimates. The solid lines in the bottom panels are local smooths using a 10% span.

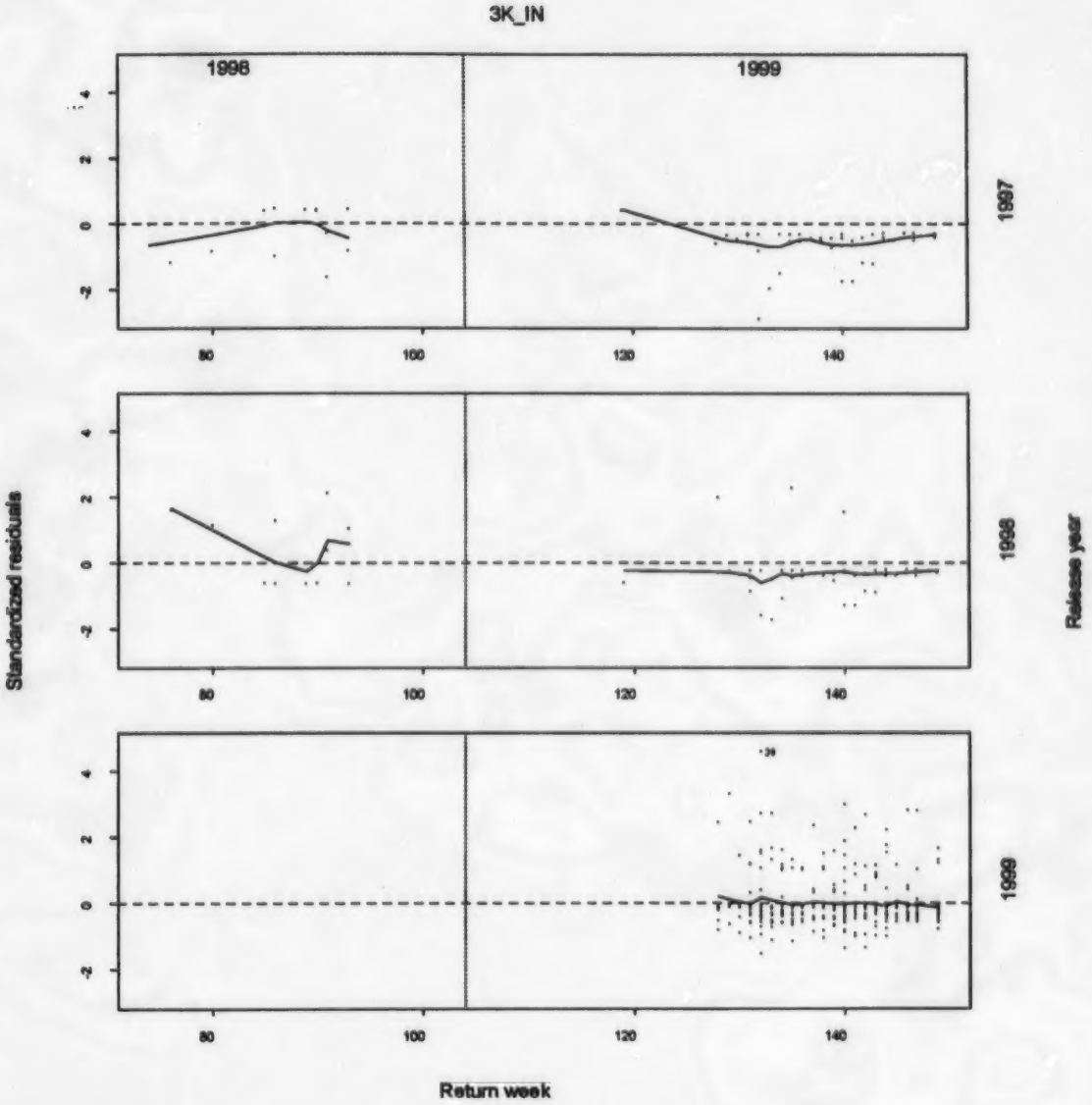

Figure 13: Standardized chi-square residuals. The solid line marks a smoother estimate of residual trends. The last 2 digits of the experiment number are shown for residuals greater than ±3. The vertical lines separate return years.

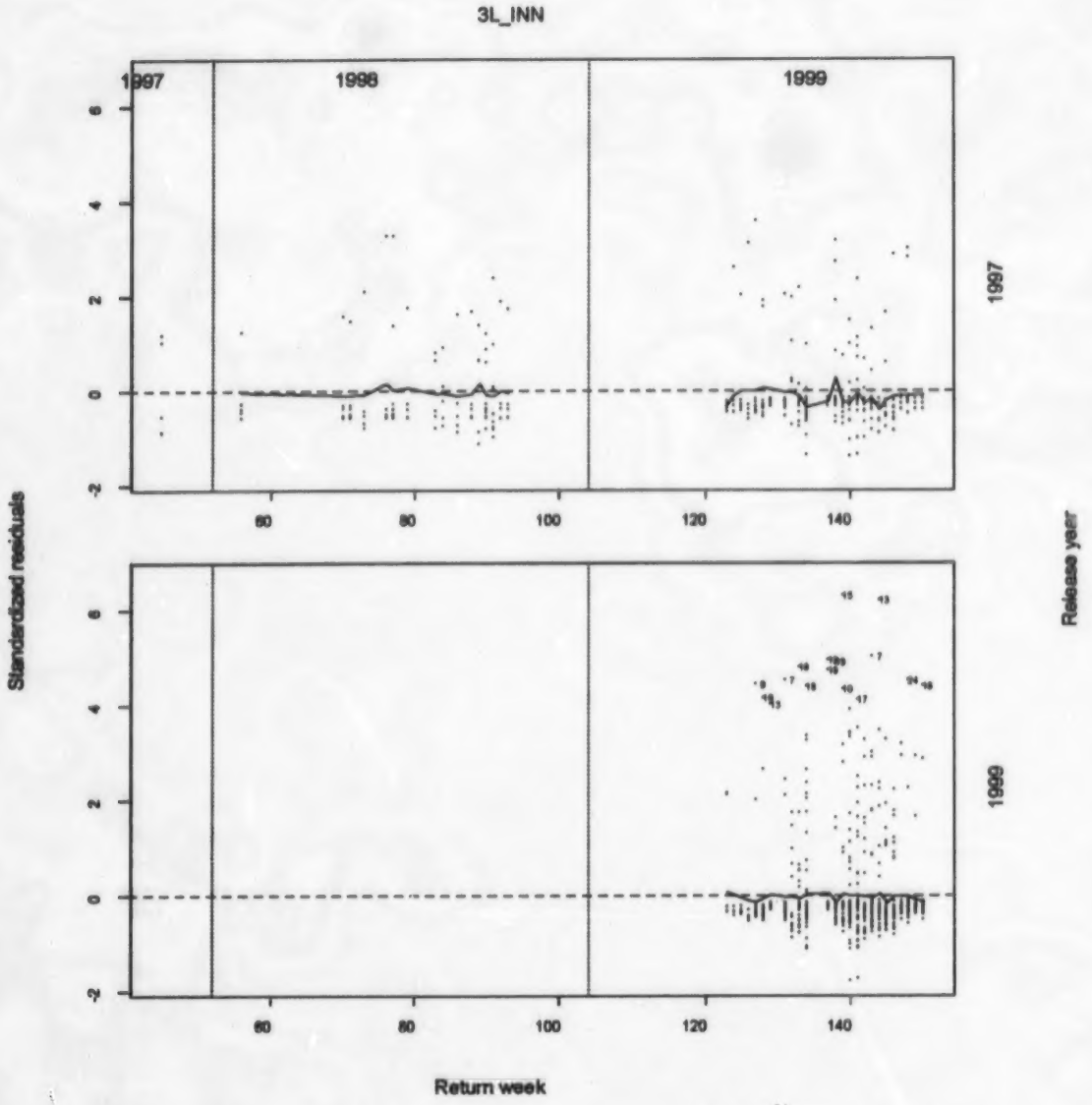

Figure 14: Standardized chi-square residuals. The solid line marks a smoother estimate of residual trends. The last 2 digits of the experiment number are shown for residuals greater than ±3. The vertical lines separate return years.

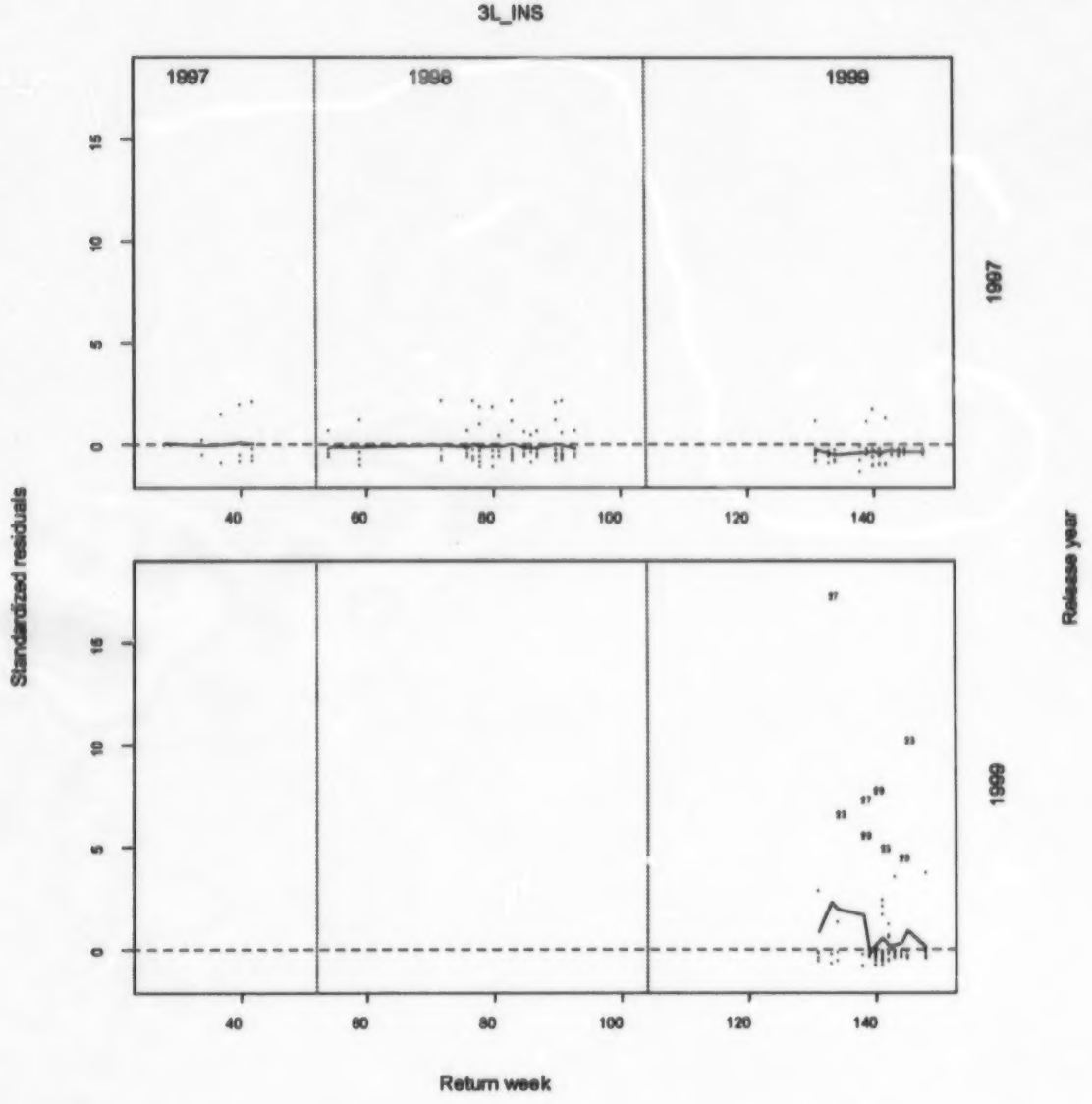

Figure 15: Standardized chi-square residuals. The solid line marks a smoother estimate of residual trends. The last 2 digits of the experiment number are shown for residuals greater than ±3. The vertical lines separate return years.

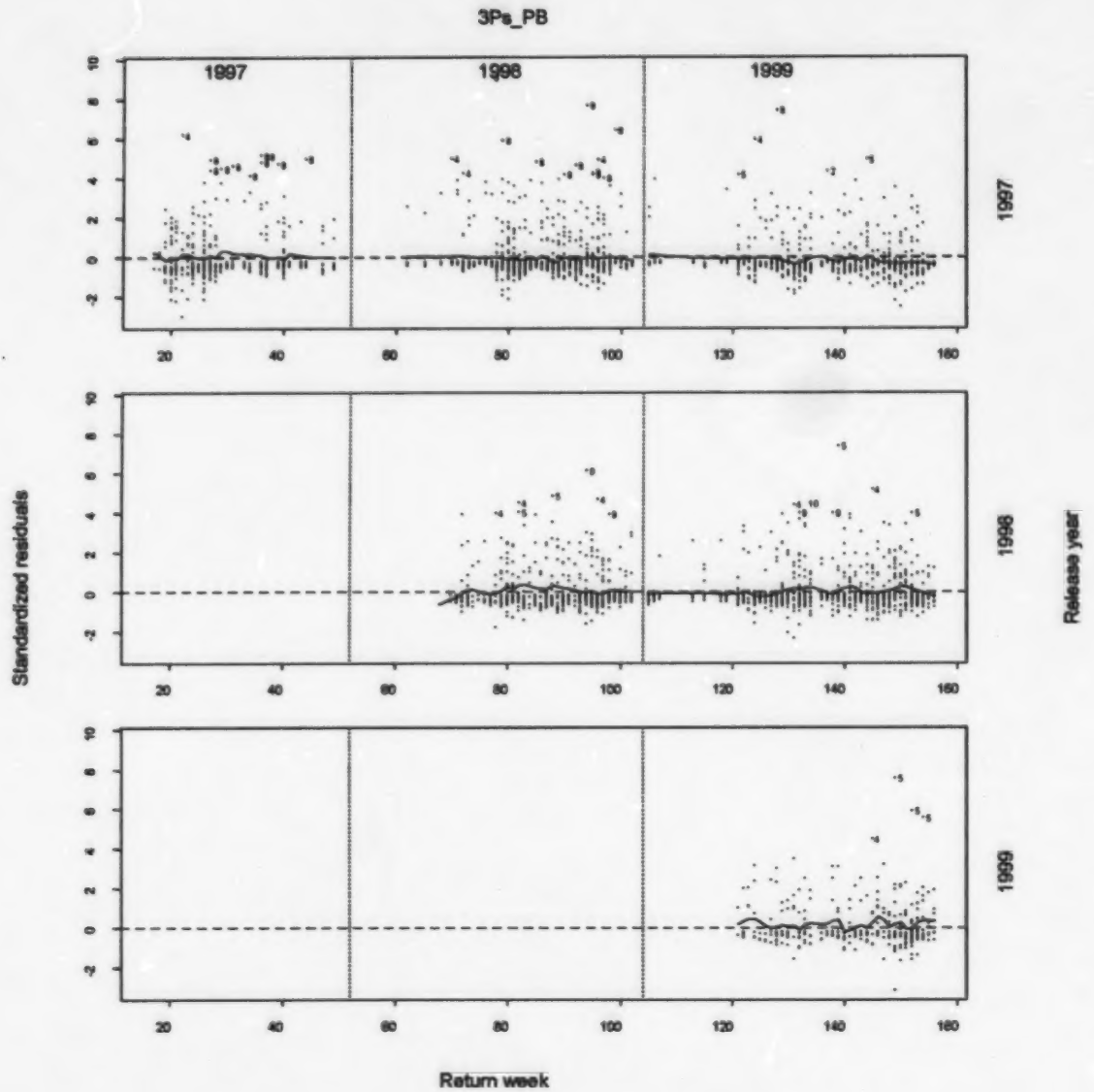

Figure 16: Standardized chi-square residuals. The solid line marks a smoother estimate of residual trends. The last 2 digits of the experiment number are shown for residuals greater than ±3. The vertical lines separate return years.

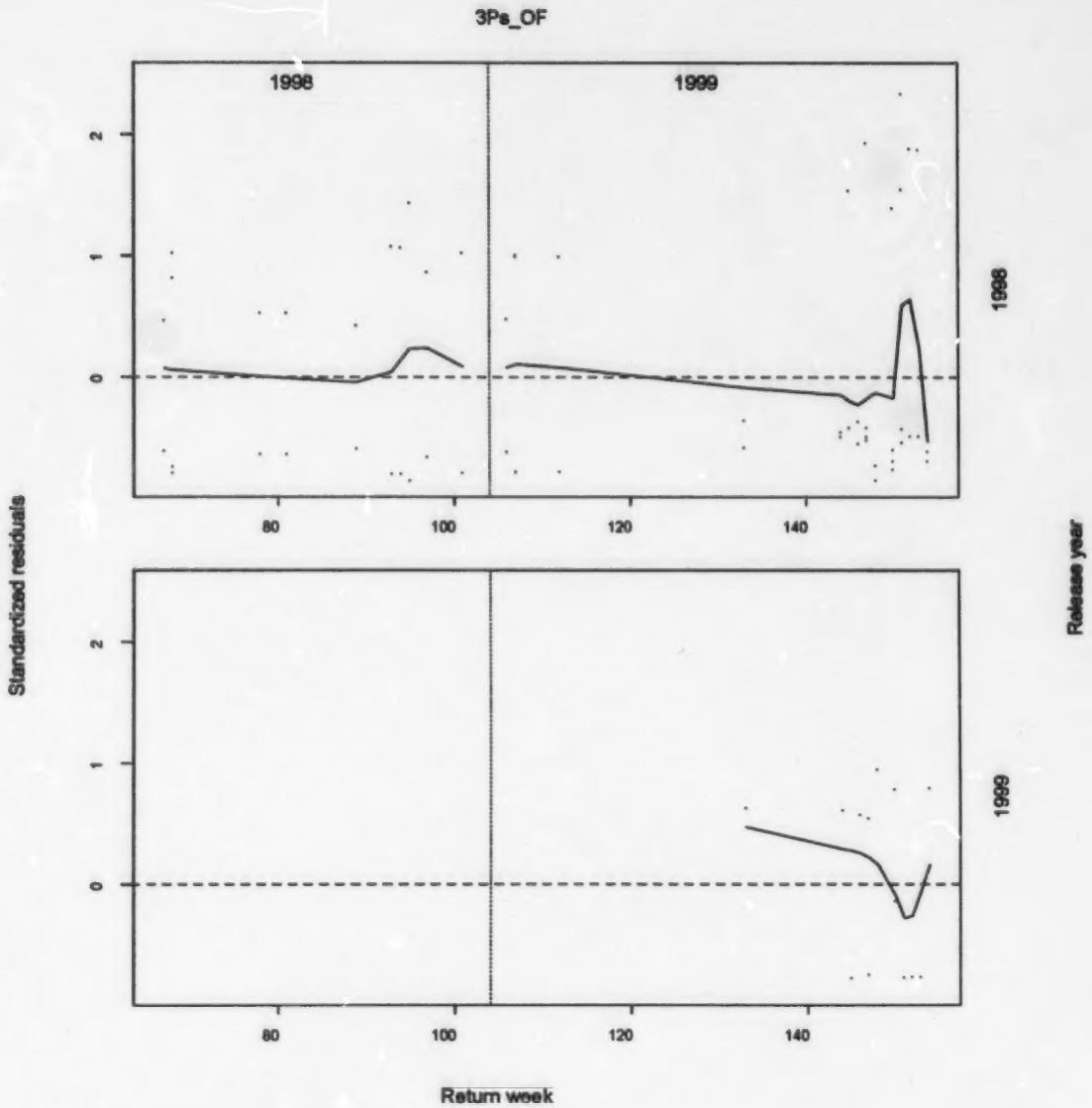

Figure 17: Standardized chi-square residuals. The solid line marks a smoother estimate of residual trends. The last 2 digits of the experiment number are shown for residuals greater than ±3. The vertical lines separate return years.

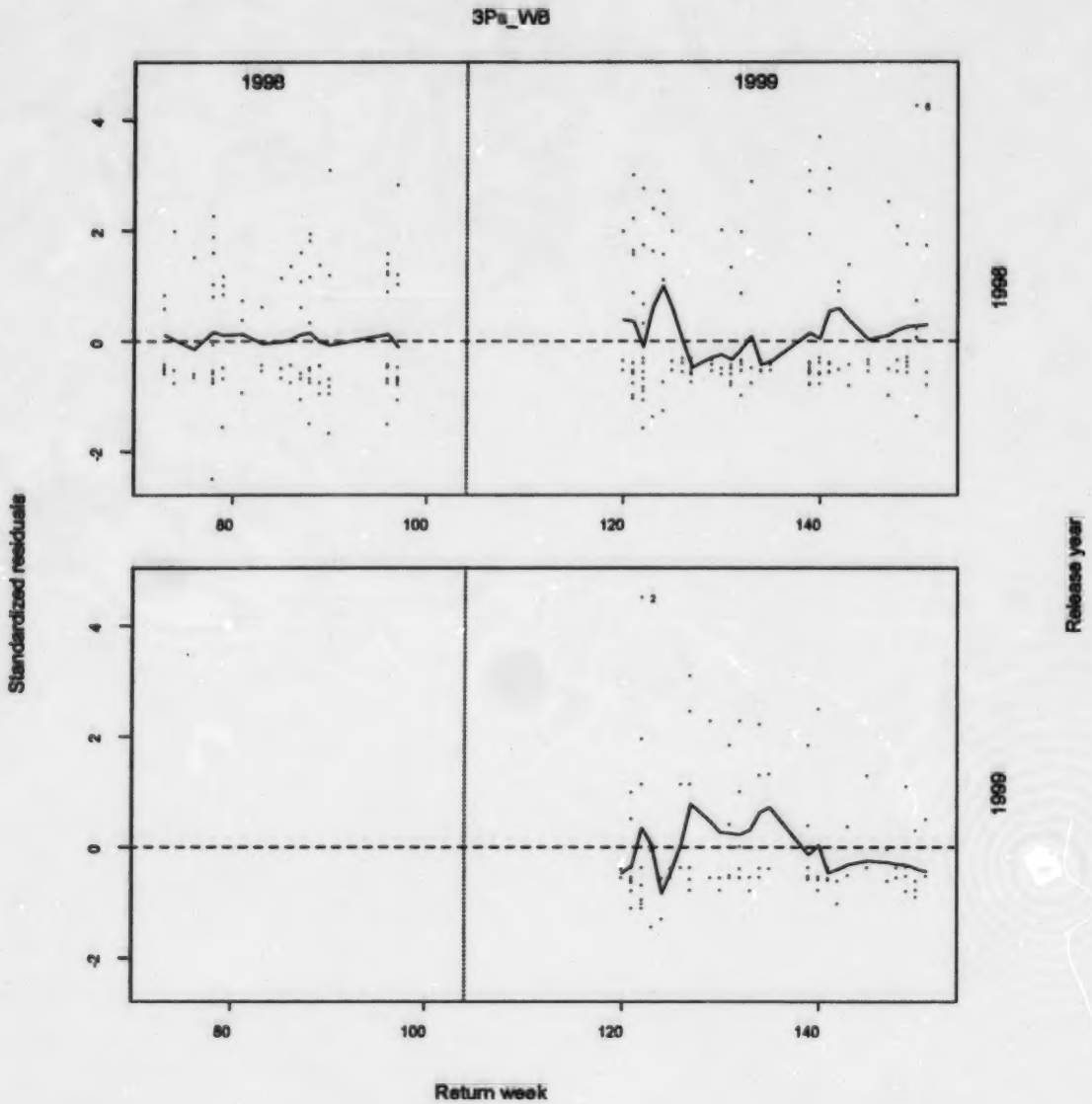

Figure 18: Standardized chi-square residuals. The solid line marks a smoother estimate of residual trends. The last 2 digits of the experiment number are shown for residuals greater than ±3. The vertical lines separate return years.

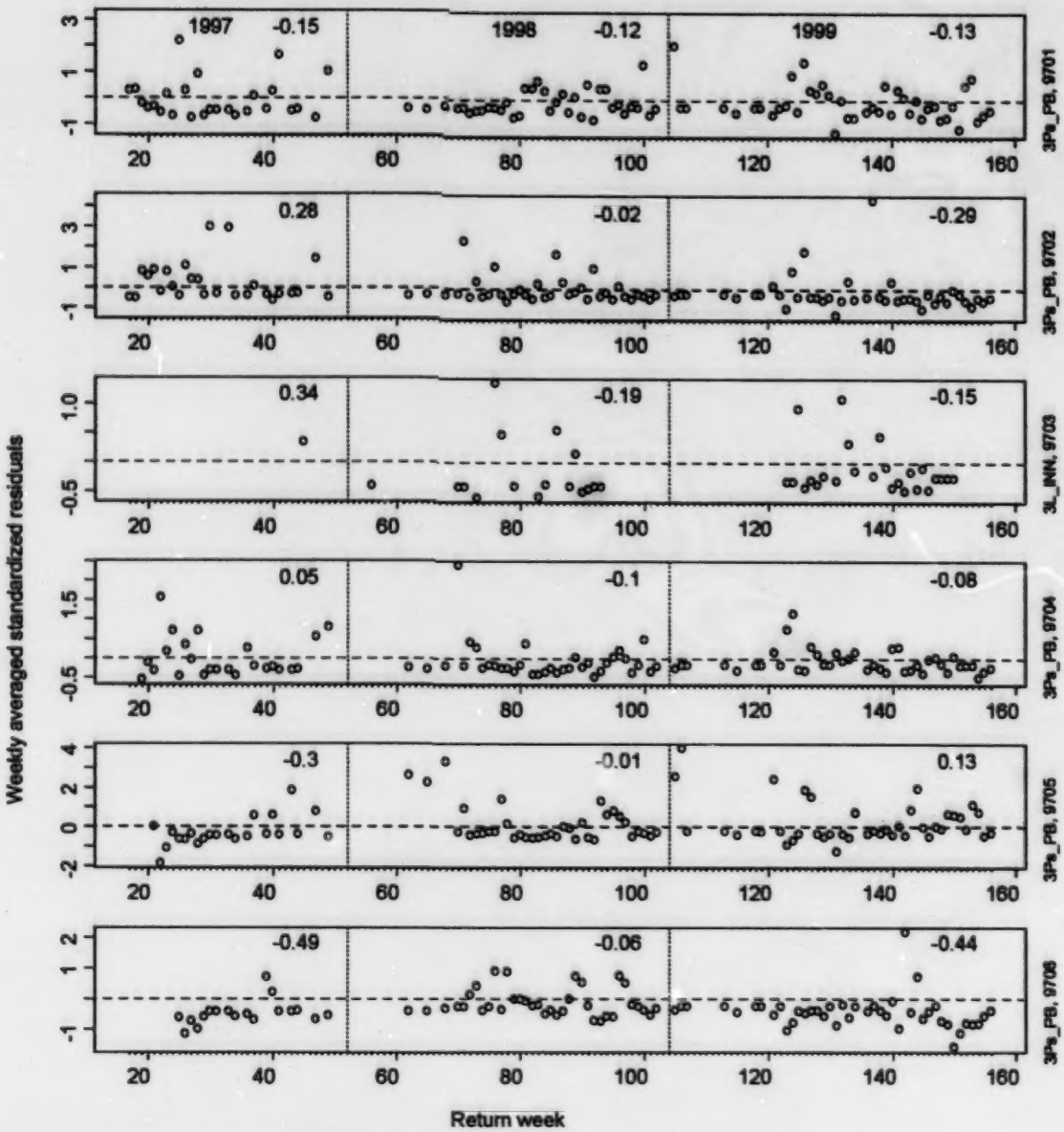

Figure 19: Standardized chi-square residuals for each experiment. The residuals are averaged over gears. Annual average residuals are shown along the top of each panel. The experiment no. and release region are shown at the right of each panel. The horizontal dashed line marks the origin. The vertical lines separate return years.

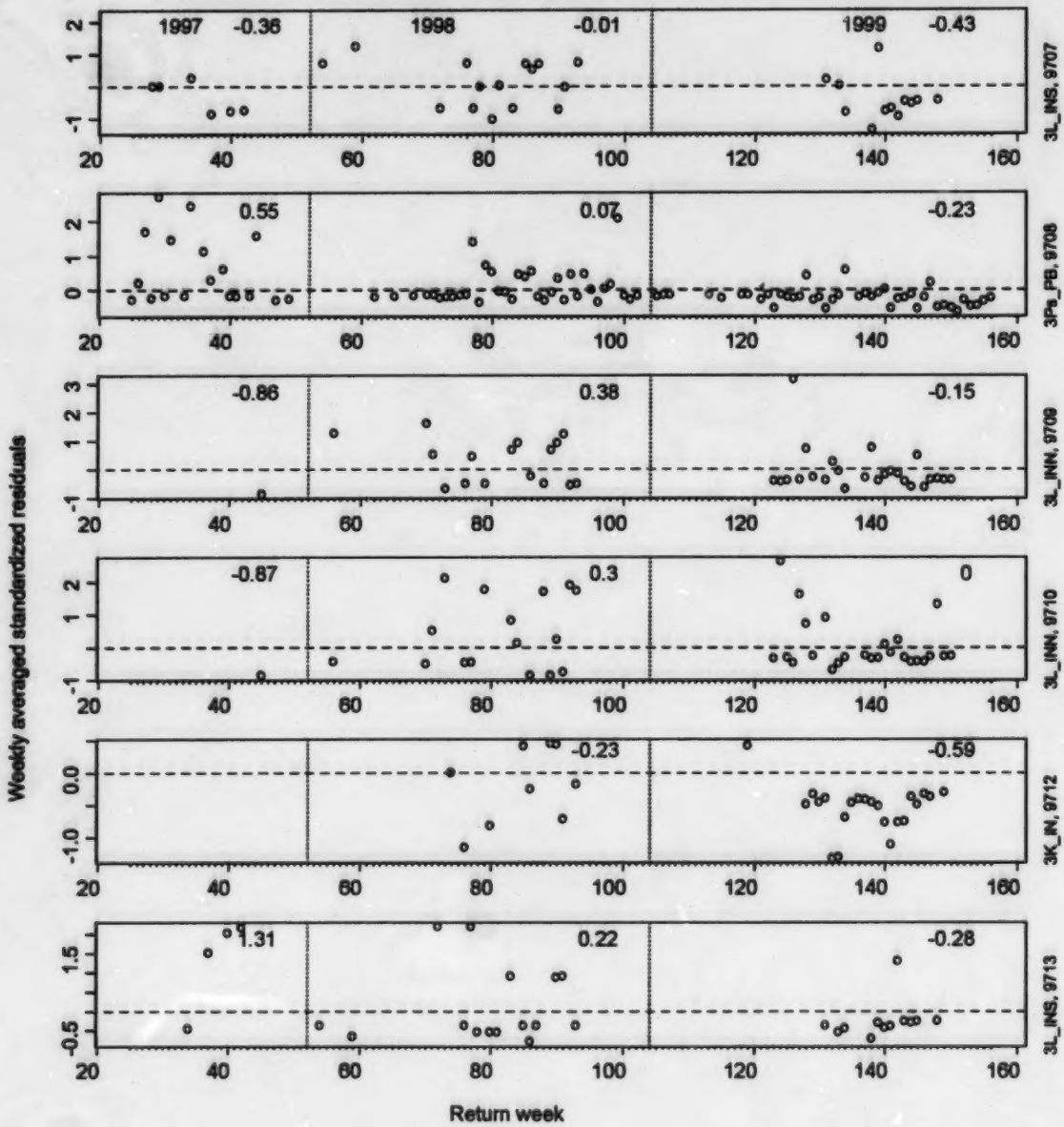

Figure 20: Standardized chi-square residuals for each experiment. The residuals are averaged over gears. Annual average residuals are shown along the top of each panel. The experiment no. and release region are shown at the right of each panel. The horizontal dashed line marks the origin. The vertical lines separate return years.

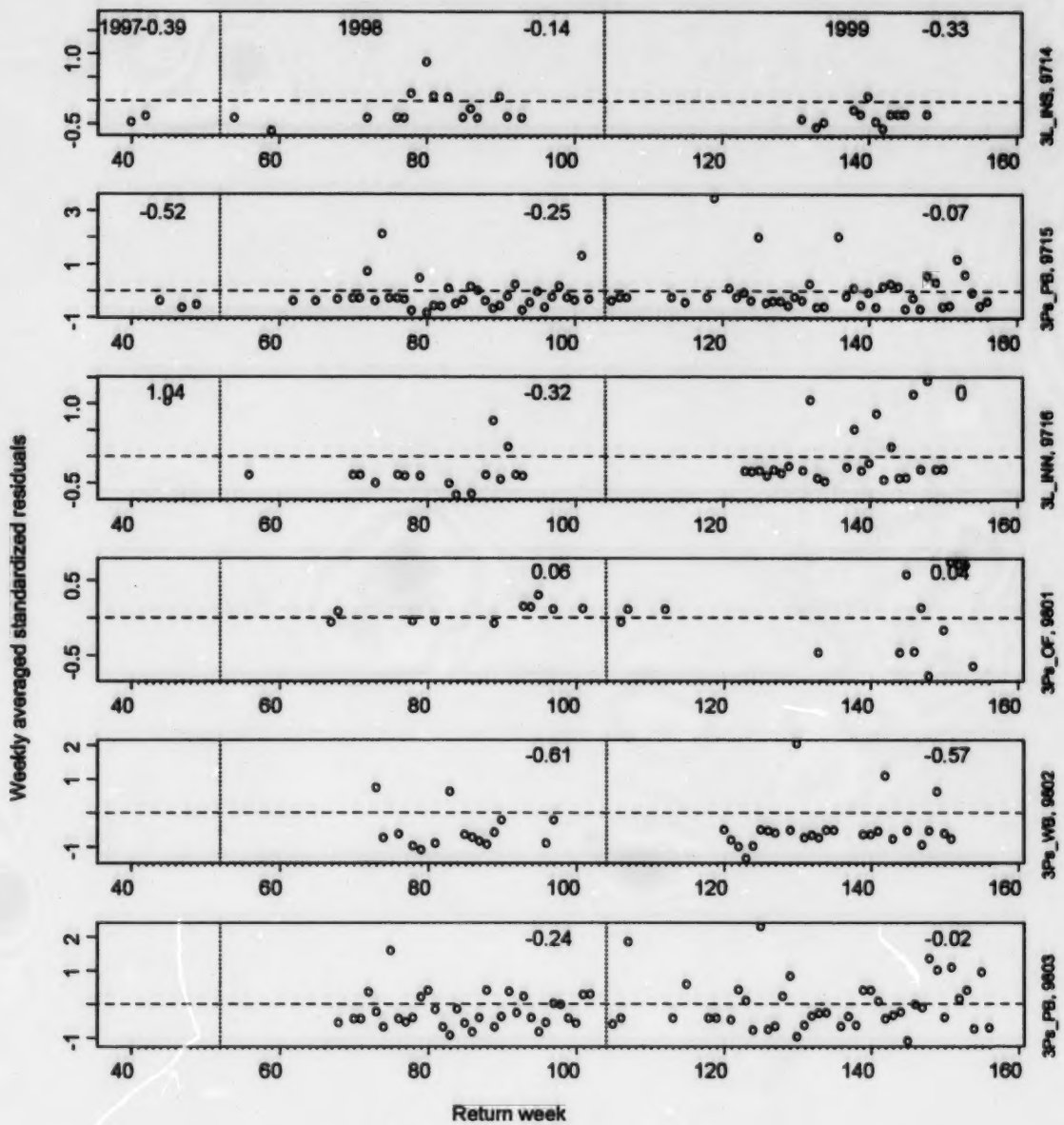

Figure 21: Standardized chi-square residuals for each experiment. The residuals are averaged over gears. Annual average residuals are shown along the top of each panel. The experiment no. and release region are shown at the right of each panel. The horizontal dashed line marks the origin. The vertical lines separate return years.

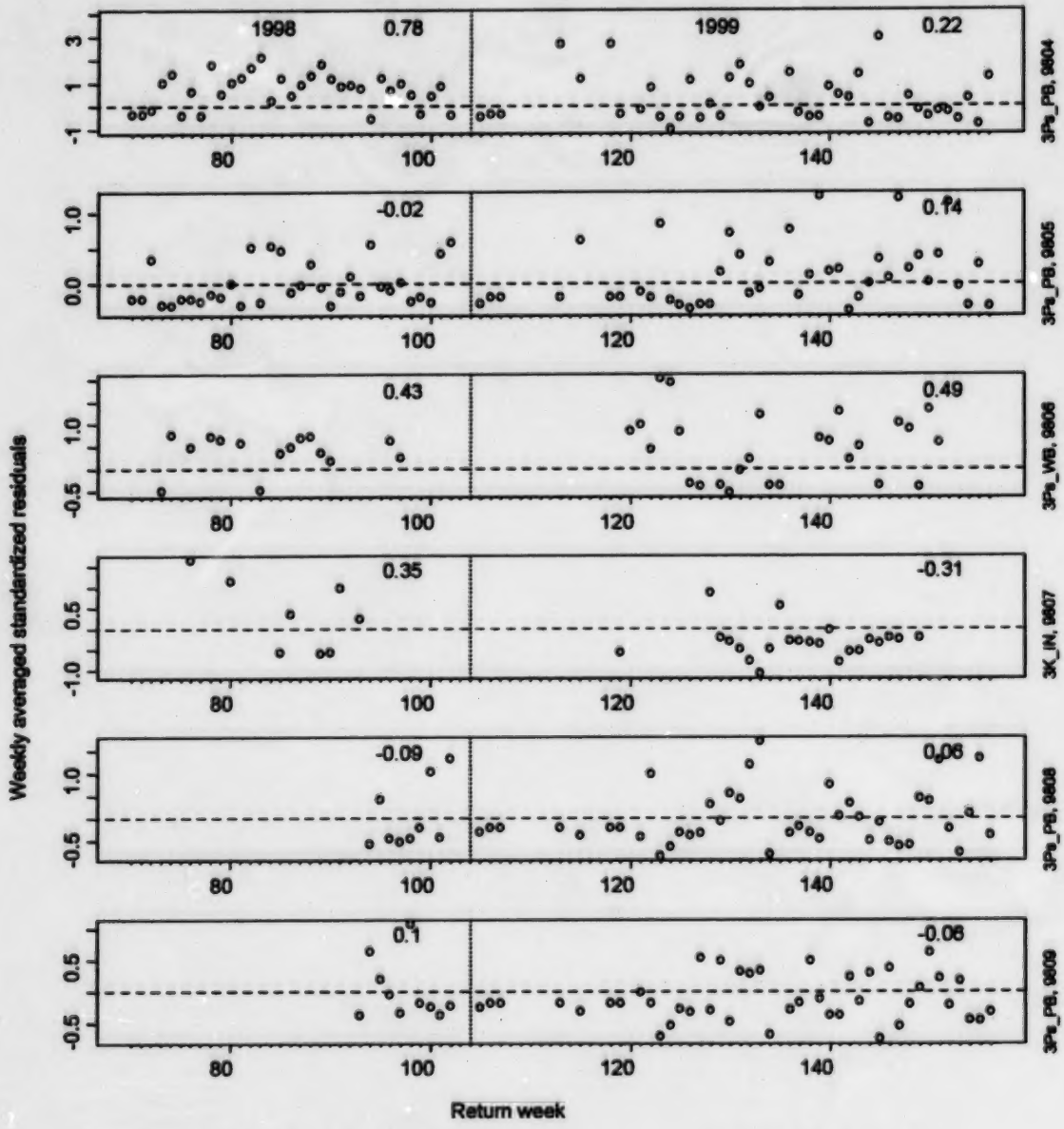

Figure 22: Standardized chi-square residuals for each experiment. The residuals are averaged over gears. Annual average residuals are shown along the top of each panel. The experiment no. and release region are shown at the right of each panel. The horizontal dashed line marks the origin. The vertical lines separate return years.

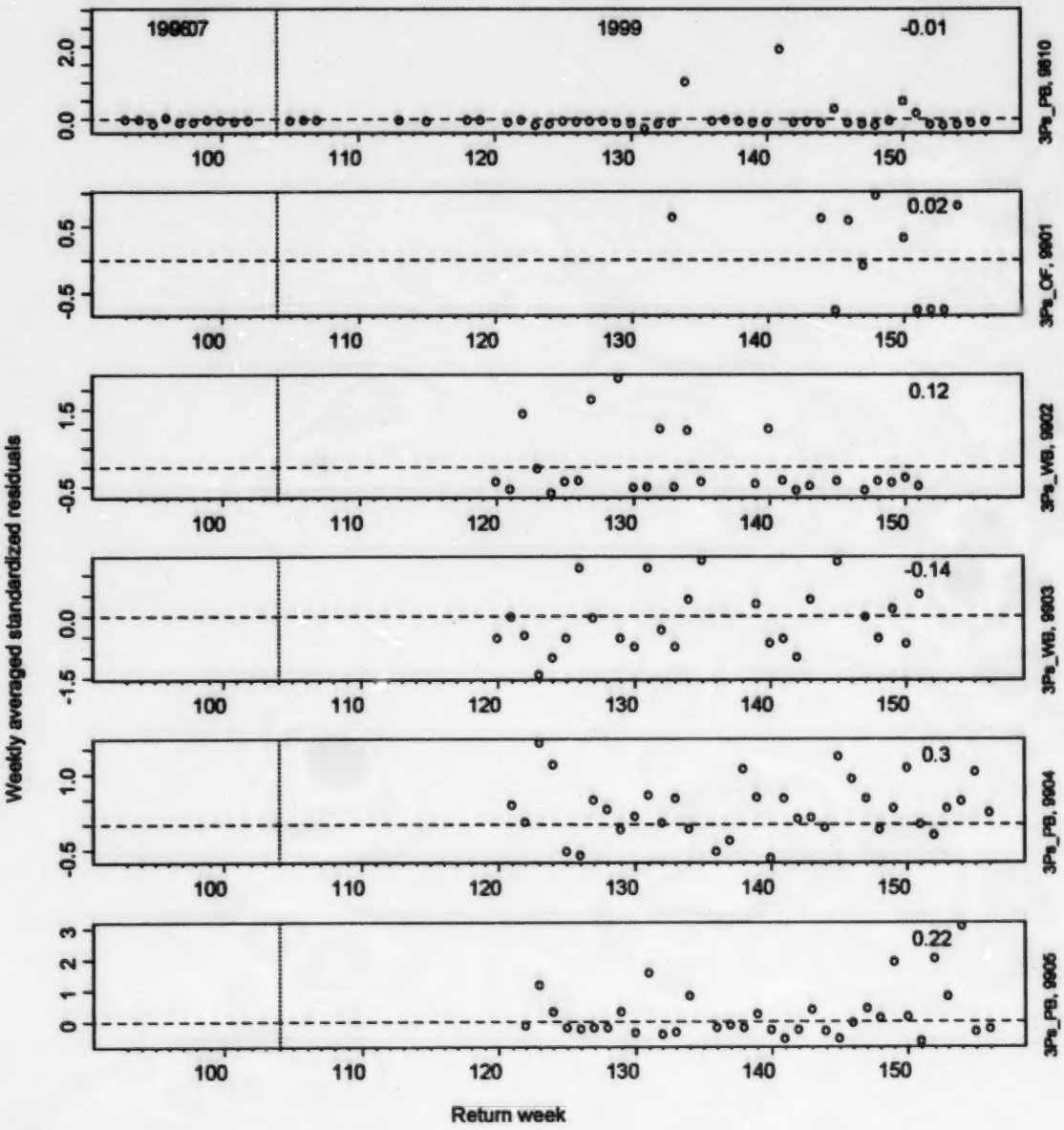

Figure 23: Standardized chi-square residuals for each experiment. The residuals are averaged over gears. Annual average residuals are shown along the top of each panel. The experiment no. and release region are shown at the right of each panel. The horizontal dashed line marks the origin. The vertical lines separate return years.

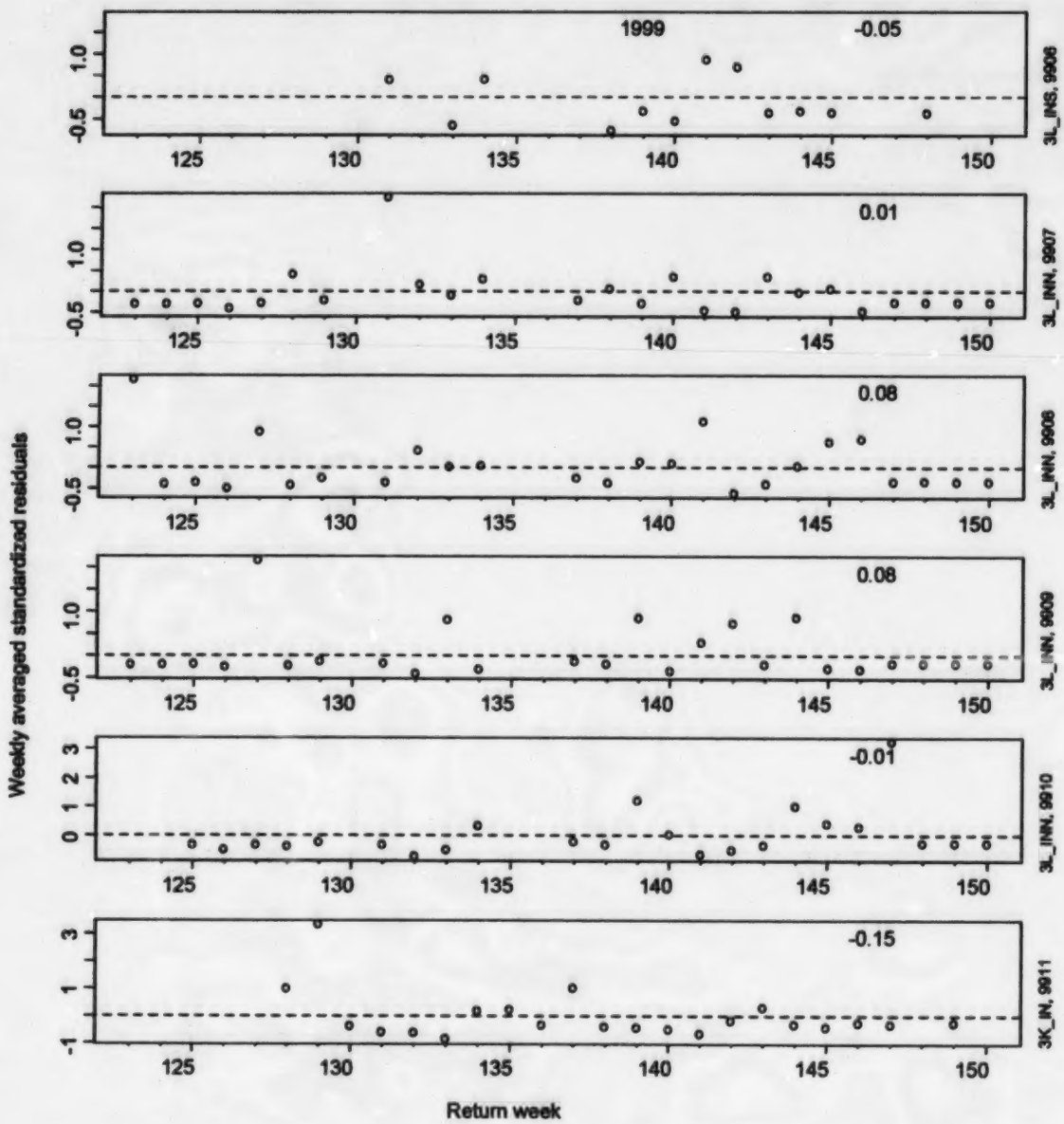

Figure 24: Standardized chi-square residuals for each experiment. The residuals are averaged over gears. Annual average residuals are shown along the top of each panel. The experiment no. and release region are shown at the right of each panel. The horizontal dashed line marks the origin. The vertical lines separate return years.

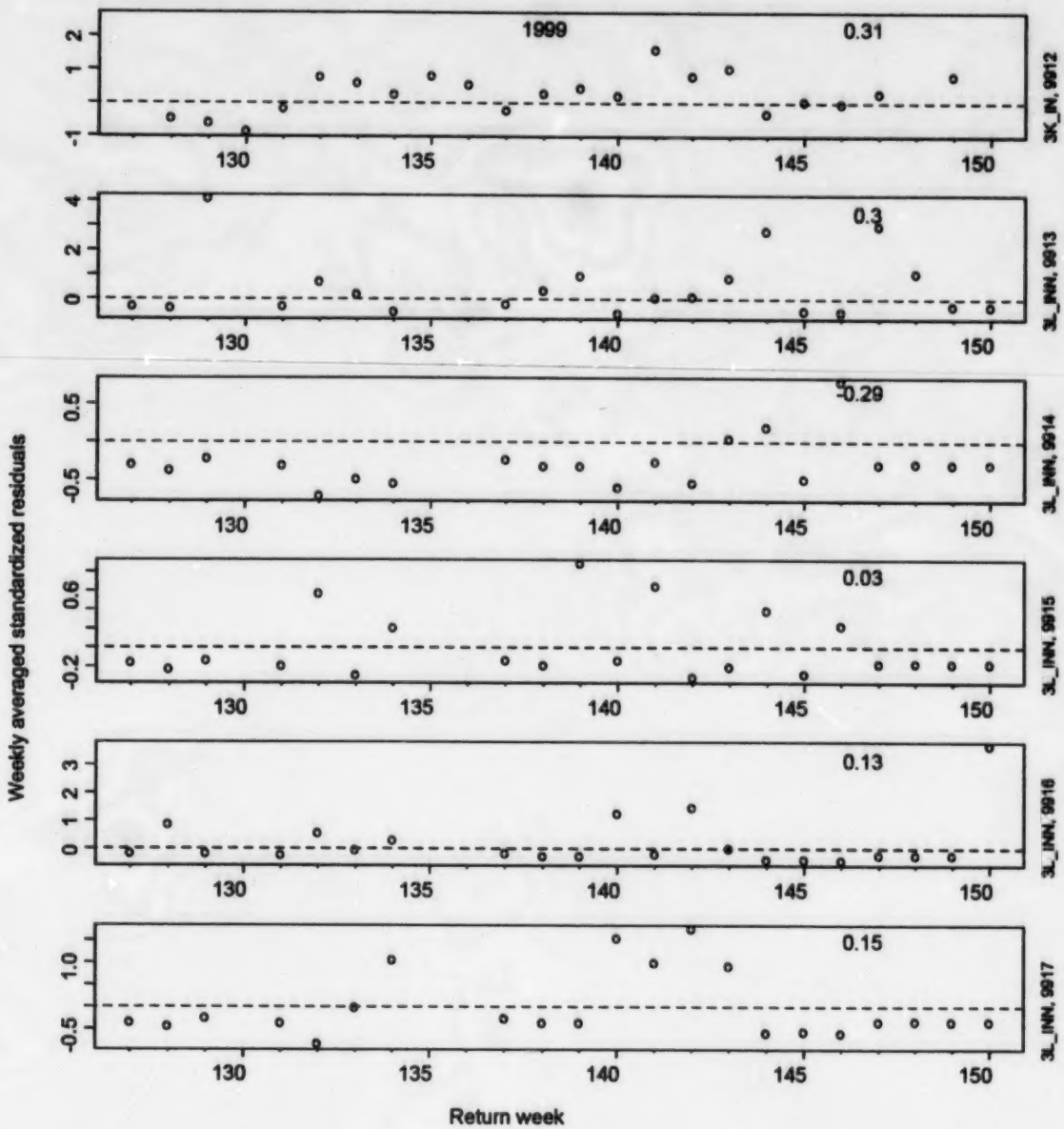

Figure 25: Standardized chi-square residuals for each experiment. The residuals are averaged over gears. Annual average residuals are shown along the top of each panel. The experiment no. and release region are shown at the right of each panel. The horizontal dashed line marks the origin. The vertical lines separate return years.

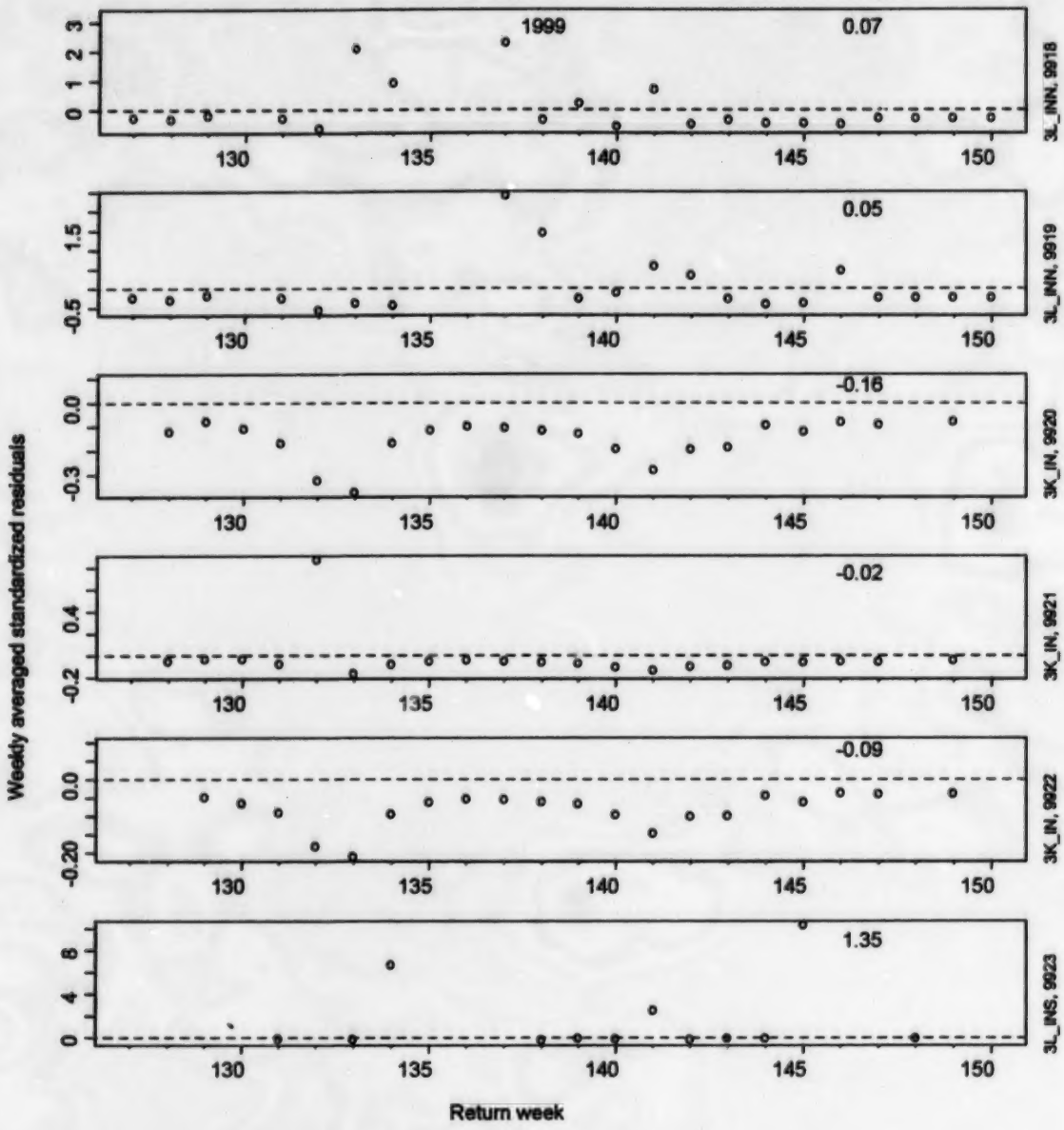

Figure 26: Standardized chi-square residuals for each experiment. The residuals are averaged over gears. Annual average residuals are shown along the top of each panel. The experiment no. and release region are shown at the right of each panel. The horizontal dashed line marks the origin. The vertical lines separate return years.

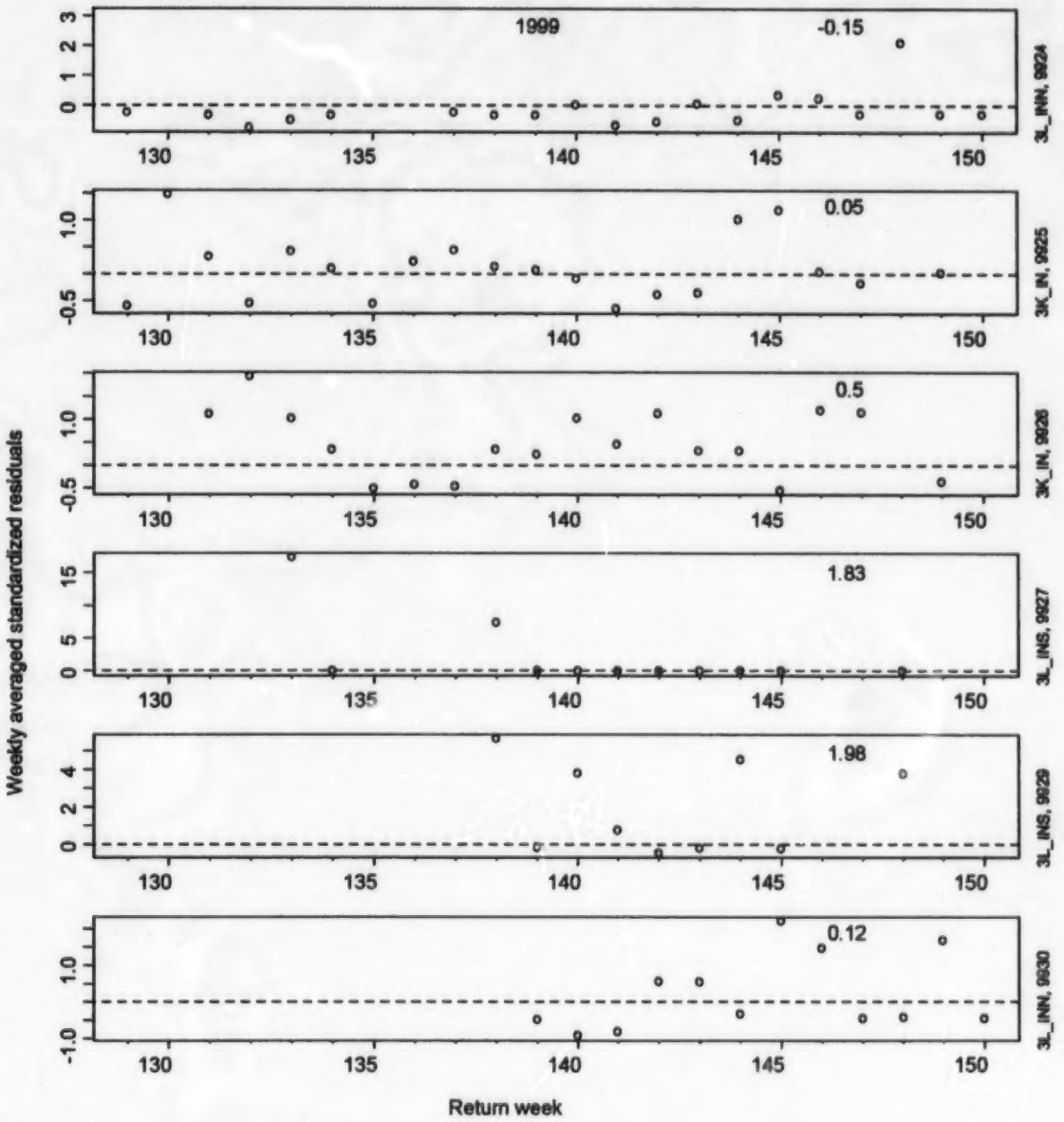

Figure 27: Standardized chi-square residuals for each experiment. The residuals are averaged over gears. Annual average residuals are shown along the top of each panel. The experiment no. and release region are shown at the right of each panel. The horizontal dashed line marks the origin. The vertical lines separate return years.

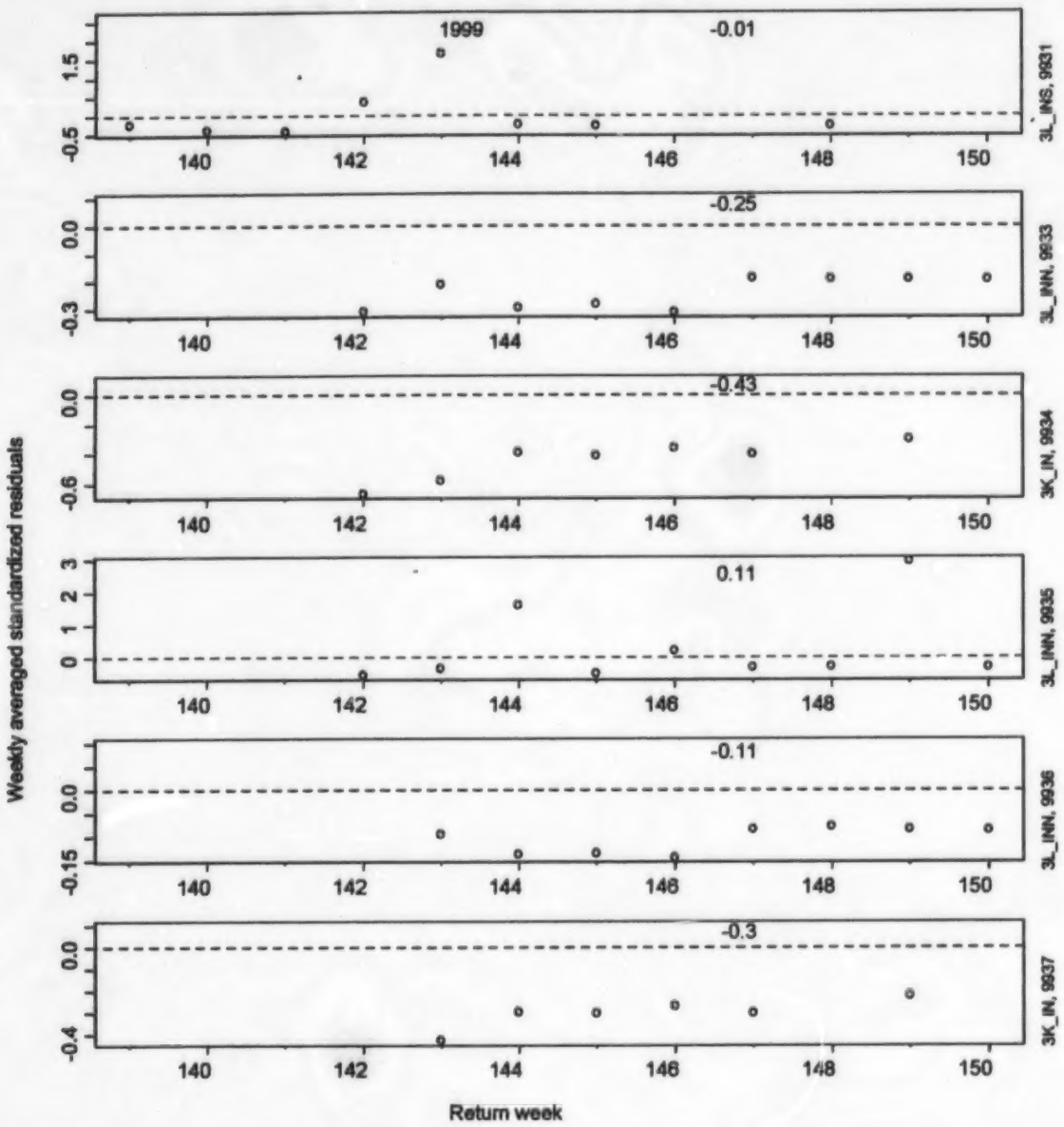

Figure 28: Standardized chi-square residuals for each experiment. The residuals are averaged over gears. Annual average residuals are shown along the top of each panel. The experiment no. and release region are shown at the right of each panel. The horizontal dashed line marks the origin. The vertical lines separate return years.

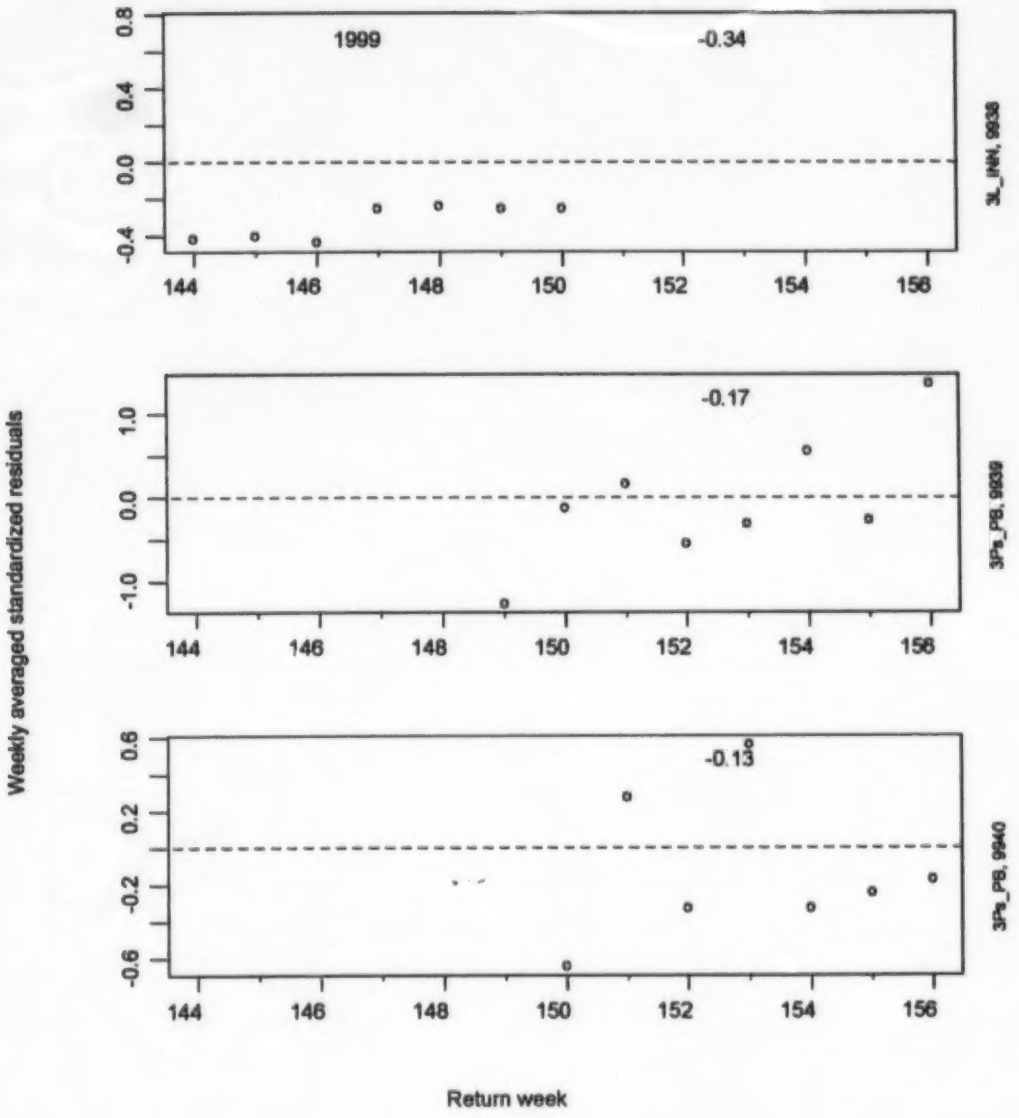

Figure 29: Standardized chi-square residuals for each experiment. The residuals are averaged over gears. Annual average residuals are shown along the top of each panel. The experiment no. and release region are shown at the right of each panel. The horizontal dashed line marks the origin. The vertical lines separate return years.